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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

STUDIES OF HUMAN DYNAMIC SPACE ORIENTATION
USING TECHNIQUES OF CONTROL THEORY

FINAL REPORT

NASA GRANT NSG-577

LANGLEY RESEARCH CENTER

1964 - 1974

PRINCIPAL INVESTIGATOR

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Massachusetts Institute of Technology

Cambridge, Massachusetts

Professor Laurence R. Young

Principal Investigator

ACKNOWLEDGEMENTS

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INTRODUCTION

This report summarizes the research performed under
NASA Grant NSG-577 from 1964 through 1974. As originally
proposed, the purpose of the grant was the study of human
spatial orientation. In addition to control theory models
for many of the sensory functions inherent in human assess-
ment of spatial orientation, several techniques for measuring
perception of orientation and for altering perceptions have
been developed. Many of these techniques can be used in
simulators and their applications within the Man Vehicle
Laboratory has considerably broadened the scope of the
original proposal. This final report covers the topics of
manual control, displays, sensory system models, medical
applications and equipment developed.

During the course of the grant a total of 20 Master's
Thesis, 2 Engineer's Theses, and 8 Doctoral Theses have
been written with its support, and numerous papers have
been presented at conferences and published in the literature.
A listing of theses is given in Appendix A. A bibliography
of papers presented and published by the Man Vehicle Laboratory
pertaining to the grant is given in Appendix B. Reprints may
Generally be obtained by writing the Laboratory, Room 37-219,
Massachusetts Institute of Technology, Cambridge, MA 02139.

Our goals were to extend the control models of the
human operator to include the description of the role of

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the non-visual motion sensors, particularly the vestibular and tactile sensors, in dynamic space orientation. These sensor systems are of vital interest, not only because of the deleterious effects of vertigo and the confusion that may exist when the visual and non-visual perceptions of oreintation disagree, but because of the control of vehicles in which the sensing of motion cues aids appreciably in the operator's control task. Primarily, the research concentrated on the investigation of the vestibular system control characteristics (semicircular canals and otoliths) and the use of motion cues in closed loop control of simple stable and unstable systems. As the research led to problems of vehicle control beyond the narrow scope of motion cues, we extended our investigations into the study of advanced display systems and continued our earlier work on eye movement control.

I

MANUAL CONTROL

N76-21893

Initial work on the manual control aspects or our experimental program led to several interesting observations on the general operator model. Although we primarily concentrated on the sensory portion of the loop, work was also done on the control and compensation aspects. In particular, we studied man's non-linear (switching) characteristics and his use of control with compatible and incompatible multiple inputs, both visual and vestibular. Other experiments were performed with pulse and bang-bang controllers and the effects of sudden changes in control stick mechanical impedance. In closing the loop through the dynamics of the controlled vehicle, we performed experiments on the limits of control of unstable vehicles with and without motion cues. The inverted pendulum controlled element, programmed as a self pacing element, was used extensively as a scalar performance index. In addition, the motorbike equations of motion were studied with regard to required human equalization. A series of publications concerned with this work appeared in 1965. They are abstracted below.

BANG BANG ASPECTS OF MANUAL CONTROL IN HIGH ORDER SYSTEMS

L.R. Young and J.L. Meiry

ABSTRACT

The tendency of many human operators to respond in a bang-bang fashion when controlling some high order system is investigated. A three mode

switch is compared with a linear control stick
and shown to permit better manual control of
systems with more lag than double integration.
In experiments requiring stabilization of a
moving base flight simulator programmed as an
unstable system (undamped inverted pendulum)
operators use the linear control stick in a
bang-bang fashion. In place of quasi-linear
models for these situations, a simple on-off
model for the human is suggested, and the
switching lines and error trajectories in the
phase plane are presented. The ability to
control an unstable system with visual and
motion cues is compared.

MANUAL CONTROL OF AN UNSTABLE SYSTEM WITH
VISUAL AND MOTION CUES

L.R. Young and J.L. Meiry

ABSTRACT

The effect of motion on a human operator's
ability to control the orientation of an
unstable vehicle was investigated. Stabili-
zation of a simulated inverted pendulum was
compared under conditions of only visual dis-
play, visual and motion cues, and only motion
cues. The results are interpreted in terms
of servoanalytic methods.

THE ROLES OF MEN AND INSTRUMENTS IN CONTROL
AND GUIDANCE SYSTEMS FOR AIRCRAFT

C.S Draper, L.R. Young, H.P. Whitaker

ABSTRACT

Control and guidance are functions that cause
vehicles to move so that their assigned missions
are successfully accomplished. Some aspects of
these functions are primarily concerned with the
collection, processing and use of intelligence
and involve only signals representing information.
For most of history these aspects have been per-
formed by human pilots. Until recent years, men
also applied their muscles to transform the low
power levels of nerve impulses to the much higher

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energies required to actuate the devices used for propulsion and maneuver in land, water and air vehicles.

Changes in the roles of human operators started when transportation developments introduced problems of control and guidance that were beyond direct solution by human abilities. Men continued to collect, process and apply information, but their senses had to be extended by instruments and their muscles needed to be suplemented by power-amplifying boosters. In addition, circumstances appeared in which automatic control and guidance had to be provided by inanimate systems because such craft as military missiles and drone aircraft do not carry men.

Astronautical craft for earth orbits and space exploration have been for the most part unmanned, but the immediate prospect of extended flights into space with human crews has stimulated very active comparison between the capabilities and limitations of men and inanimate devices for use in control and guidance systems.

In this paper, the authors discuss the essential elements of control and guidance and review typical system configurations ranging from completely manual operation to arrangements with optional automatic action under the command of on-board and remote human monitors. The abilities of pilots to sense information, to carry out acts of skill, to evaluate data, to reach wise decisions, and to implement these decisions are considered from the standpoint of overall control and guidance performance. The conclusion reached is that the optimum system for extended space operations should be basically automatic and able to perform without help from remote equipment, but should also have provisions for on-board monitoring and optional operation by human pilots. For the purposes of information exchanges, the system should include provisions for radio and radar links with ground based installations.

The Apollo Spacecraft Guidance System, which will soon be used for manned exploration of the moon, is described as a practical mechanization of the principles which are discussed.

COMPARISON OF RELAY AND MANUAL CONTROLLERS
FOR SYSTEMS WITH HIGH ORDER DYNAMICS

P.S. Kilpatrick

Bachelor's Thesis

Department of Aeronuatics and Astronautics
1964

ABSTRACT

This thesis compared a human operator's
ability to control high order systems
using linear and relay controllers. The
subject operates the control sticks to
minimize the displayed error in a comp-
ensatory tracking problem. The distur-
bance or forcing function consisted of
filtered white noise. The controllers
compared by computing the average integ-
ral square of the error signal for tracking
runs on different systems. The results
show the relay controller to be superior
for a system with a transfer function
relation of $k/p^2(p + 1)$. The results
were not conclusive for the less diffi-
cult systems, k/p^2 and $k/p^2(p/3 + 1)$.

HUMAN RESPONSE TO VARIATIONS OF SIMULATED
CONTROL STICK FORCES

I.S.C. Johnson, Jr.

Bachelor's Thesis

Department of Aeronautics and Astronautics
1964

ABSTRACT

A second order control stick system was de-
signed and built. A d.c. reversible torque
motor was used to provide the stick force.
Efforts to achieve variability of dynamic
force coefficients were hampered by the
motor's delayed reaction to input current
signals and need of a threshold current
before producing any torque.

The magnitude of the stick forces was changed
without foreknowledge of the tracker in a pur-
suit problem. The induced error in tracking

was taken as a measure of the importance of stick force for accurate tracking. Conclusions were that stick force is beneficial to the operator. Spring force information was found to be of most use. The magnitude of error induced by stick force was independent of whether the force was decreased or increased. Largest disruption of tracking accuracy occurred when all force information was removed.

Possible reasons for the apparent minimization of force information importance at low frequencies were presented. The suggestion that the natural damping of the stick system is a critical variable was also forwarded.

1.1.1   Adaptive Control

Several aspects of the characteristics of the human as an adaptive controller have been considered in our attempt to establish the principal types of adaptive control and to set forth the requirements for optimum man-machine adaptive control. One of the first comprehensive works to come from this research was a paper entitled "Adaptive Functions of Man in Vehicle Control Systems" by Y.T. Li, L.R. Young and J.L. Meiry, presented to the International Federation of Automatic Control (Teddington) Symposium on the Theory of Self-Adaptive Control Systems, September 1965 and published in the Theory of Self Adaptive Control Systems.

ADAPTIVE FUNCTIONS OF MAN IN VEHICLE CONTROL SYSTEMS

Y.T. Li, L.R. Young, J.L. Meiry

ABSTRACT

Inability of human pilots to introduce adequate adaptation of their control provided much of the motivation for the development of automatic adaptive control systems. The rapid change in aircraft, which may climb from sea level to extreme altitudes in minutes, required automatic adaptive control to relieve the burden on the operator.

This paper examines the principles and composition of existing automatic adaptive control systems and on these, bases the human adaptive as well as primary control functions are analyzed.

In general, the human outshines the automatic system with his huge capacity for open loop or programmed control; but he lacks the capacity and speed for making on-line computations needed in the operation of an active continuous adaptive system. Humans can also perform some passive type of very simple active adaptation, but would require the assistance of a computer to perform complicated active adaptation.

This limitation is responsible for the dominance of mechanized systems for adaptive control. There are advantages attributable to a computer-assisted human adaptive control system considering the huge capacity of man's open loop adaptation. Visual or some other form of multi-input display becomes a necessary medium when computer-man coupling is to be made effectively. Considering man's remarkable ability of pattern recognition, this task may be in many cases easier than the coupling of a computer with an automatic actuator when a complicated function is to be recognized and manipulated.

Further work led to the design of practical automatic adaptive systems. The first of these was published as the Master's Thesis of Syozo Yasui.

THE USE OF THE CHATTER MODE IN SELF ADAPTIVE SYSTEMS

S. Yasui

Master's Thesis

Department of Aeronautics and Astronautics
1967

ABSTRACT

In an on-off relay control system under the chatter mode, the average motion of the plant is completely determined by the equation of the switching function. This fact has been applied in self-adaptive control systems in which the switching function describes the model dynamics and the chatter mode is reached. The proposed policy of forward gain (switching level) adjustment takes into account the reduction of chatter frequency and of the control force magnitude, in addition to the sustenance of the chatter mode. A simple two-dimensional display is used for manual operation and/or monitoring.

Several examples are presented to demonstrate the analog computer simulation. The results show satisfactory performance of the gain adjustment mechanism.

Known self-adaptive control systems are outlined with emphasis on those using a relay as a key element, and extended application to a class of distributed parameter control systems is considered. As a byproduct of this study, a numerical method without numerical integrations is proposed for the solution of ordinary differential equations.

The modelling of man as an adaptive control element was explored in an invited tutorial paper by Professor Young presented at the IEEE-ERS International Symposium on Man-Machine Systems, Cambridge, England in September 1969 and

published in Ergonomics and the IEEE Transactions on Man

Machine Systems in 1969, entitled "On Adaptive Manual

Control". This paper points out some of the answers,

but many more of the questions about what information man

uses in his adaptive process. In the course of research-

ing this paper, several preliminary experiments were

carried out. Three tracking situations were explored. One

operator controlled a compensatory display and was asked

to recognize and correct a sudden change in plant dynamics.

The second operator was given the same situation as the

first, with the exception that, without his knowledge, his

control stick was disconnected and the error he observed

was that generated by the first operator. The third oper-

ator merely observed the error display. Each indicated

the time when he detected a change in the plant dynamics.

Whereas the first operator could act as a model reference

adaptive control system based on an internal model of the

plant, the second could only operate on the basis of an

internal model of the entire forward loop and the third

could only adapt on the basis of error pattern recognition.

The preliminary data shows that the first operator has a

shorter detection time than the second, and both detected

the plant failures much more rapidly than the third, thus

strengthening the belief in some type of model reference

control rather than error pattern recognition adaptive

control. At the end of this grant, an extensive formal

experiment verified this result. A paper is being prepared

by L.R. Young and A. Tada summarizing the results. Both

of these papers are abstracted below:

ON ADAPTIVE MANUAL CONTROL

L.R. Young

ABSTRACT

Experimental studies and control descriptions
of the human operator in recent years have
extended the knowledge of adaptive behavior in
manual control from vague generalities about
his versatility to quantitative descriptions.
Considerable data have been gathered on the
ability of the human to adapt to changes in
input spectra, controlled element gain, polar-
ity and dynamics, display modality, and the
limits of controllability under a variety of
situations. These results have indicated a
greater adaptation versatility than expected
from some of the earlier descriptions, but
have also pointed out some of the restricted
training conditions under which the rapid
human adaptation may be expected to be demon-
strated.

When it comes to explaining how the human
manages his remarkable adaptation abilities,
less progress has been made. Improvement of
the techniques for dynamic measurement of the
adaptive process have been helpful in this
regard, but still fall short of what is re-
quired to observe the change in control law.
Some appealing suggestions for detection
models, model-reference control analogs and
statistical decision theory pattern recog-
nition algorithms have been put forth but are
in no sense "proven".

Primarily as a result of the measurement
limitation and the lack of sufficient know-
ledge about adaptive control systems in
general, the development of models for human
adaptive control has been limited to general
"schema" at this time.

THE ROLE OF HAND MOVEMENT INFORMATION FOR THE SUBJECTIVE DETECTION OF A CONTROLLED DYNAMICS CHANGE IN ADAPTIVE MANUAL CONTROL

A. Tada and L.R. Young

It is well known that a human controller adapts
rapidly to a sudden change in the dynamics of
the controlled element in a compensatory track-
ing system. This paper shows that the subject-
ive detection of the change depends on both the
tracking error and hand movement information.
Hand movement information had formerly been con-
sidered only as an output of the human controller.

An experiment which disturbed the relationship
between hand movement and tracking error was
formulated. Three subjects, an active controller,
a shadow controller and a monitor observe the
same tracking error when a change in controlled
element dynamics occurs. While the active con-
troller has real hand movement information, the
shadow controller has false hand movement infor-
mation and the monitor none.

The detection time is examined in two ways:
the time history of the detection ratio and
the correlation between subjects. The results
clearly show the dependency of the controller's
detection on the hand movement information.

Experiments with an adaptive tracking task in which
the controlled element dynamics adapt to the operator's
ability to control have been carried out in many ways. The
tasks provide a rapid measure of the operator's overall con-
trol ability. One such effect studied, in conjunction with
a pilot experiment by the Department of Nutrition and Food
Science, was the effect of a no-protein diet on the human
operator's tracking abiltiy. The results of this study are
summarized in the memo abstracted below:

A STUDY OF THE EFFECTS OF A NO PROTEIN DIET AND
CONTROL STICK VARIATIONS ON MANUAL TRACKING
PERFORMANCE FOR A SYSTEM WITH ADAPTIVE UNSTABLE
DYNAMICS

P. Kilpatrick and L.R. Young

ABSTRACT

The purpose of this experiment was to study
the effects of a no-protein diet on a human
operator's ability to perform a difficult
manual tracking task and to compare the
merits of a linear, on-off, and pulse type
of control stick.

The test required the subjects to control an
inherently unstable system. The level of
system instability changed during each track-
ing run depending on the subject performance.
The instability increased if the subject held
the displayed error below a criterion level
and decreased if the subject made errors
larger than the criterion. The system was
designed to automatically adjust to the
maximum level of difficulty the subject could
control. This task may be visualized as
similar to balancing a variable length inverted
pendulum. The pendulum length became shorter,
more difficult to balance with good performance
and longer, less difficult to balance with poor
performance.

Presumably any adverse dietary effects on
coordination or reaction time and performance
differences beteen control stick would be
more evident when the subject was forced to
operate at the limits of control.

The dietary effect was studied by comparing
the performance of a control and diet group
before and at the end of a five-day diet.
Each group consisted of five MIT undergraduates.
During the testing period, the control group
followed their normal daily routine, while the
diet group was kept under supervision by the
Department of Nutrition and Food Science.

Performance was measured by computing the
average level of instability attained during
each run and the average control stick output

necessary to control the system. A constant
stick output applied a constant torque or an-
gular acceleration to the unstable system.

Briefly, the results indicated minor dietary
effects and that the linear controller was
superior to the non-linear controller for
this task.

This measurement technique was a precursor to the useful

"critical task" control of Jex and his colleagues.

1.1.2 Effects of Roll and Yaw Motion

Attempts to develop a quantitative description of the

effects of motion cues on human operator describing functions

with the goal of extending fixed base data to predict man-

machine characteristics in flight have been carried out through

the entire period of the grant. An extensive study of roll and

yaw motion cues was carried out early in the study by R.S.

Shirley as part of his doctoral research. He used the NE-2

Pitch Roll Simulator (descibed under Equipment) for these

experiments. In order to isolate the motion cue effects in

terms of semicircular canal versus otolith contributions,

another series of experiments was carried out comparing yaw

to roll motion. The first set of experiments was presented

at the Fourth Annual NASA University Conference on Manual

Control in 1968 and is summarized in the Sc.D. Thesis of

R. Shirley, while the later experiments are summarized in

the Master's Thesis of Peter Dinsdale. Professor L.R. Young

prepared a summary paper on motion cues which was published

in the Journal of Spacecraft and Rockets in 1967 and contained

much of the groundwork for the experiments which followed. The

papers and related theses are abstracted below.

SOME EFFECTS OF MOTION CUES ON MANUAL TRACKING

L.R. Young

ABSTRACT

Although sustained high acceleration or vibra-
tion can have a deleterious effect on a pilot's
tracking ability, there are some situations in
which motion cues, as felt in flight or moving
base simulation, provide a significant improve-
ment in pilot performance. The first of these
situations is in a control task requiring more
lead compensation than is easily developed from
visual displays. The vestibular and tactile
sensations contribute velocity and acceleration
information which is used in stabilization.
Experiments on control of inverted pendulums
and VTOL's with and without motion cues are
discussed. Tests of labyrinthine defective
patients on similar tasks demonstrated the
critical importance of vestibular inputs. The
second situation required rapid adaptation to
controlled element failures in a simulated
blind landing experiment. Other tests showed
motion effects to be important in a class of
flexible booster problems. These results were
combined with many comparisons of fixed-base-
moving-base simulation experiments in the
literature to arrive at some general conclusion
regarding the effects of motion cues on tracking.

MOTION CUES IN MAN VEHICLE CONTROL

R.S. Shirley

Sc.D. Thesis
Department of Aeronautics and Astronautics
1968

ABSTRACT

An investigation is made to determine how the
human operator makes use of roll motion cues
in a man-vehicle control system. To this
purpose, the human operator's describing func-
tion is measured over a wide range of vehicle
dynamics and under conditions of visual inputs
only, motion inputs only, and combined visual
and motion inputs. Both describing function
(amplitude and phase of the human operator's
output relative to his input) and the remnant
(power spectral density of that part of the
human operator's output which is uncorrelated
with his input) are measured as a function of
frequency. The relative integral squared
error is also measured. Visual inputs are
made by means of a dot moving laterally on an
oscilloscope, and roll motion inputs are made
by means of a motion simulator.

An analytical method of correcting the exper-
imental measurements for errors introduced by
the remnant is developed and applied to the
data. The corrections are generally small.

Examination of the describing function data
leads to some conclusions about the human
operator's use of angular motion cues in a
man-vehicle control system. When the roll
motion cues are added to the visual cues,
the human operator is able to increase his
lead in the frequency range above one radian
per second. This permits him to increase his
gain and crossover frequency without decreas-
ing his phase margin. The net effect of
these changes in the human operator's control
behavior is to increase the open loop gain
without a loss of stability, and thus to
reduce the relative integral squared error
for the closed loop system.

The percentage reduction of the relative
integral squared error upon the addition
of motion cues to the visual cues varies
as a function of the controlled vehicle
dynamics. The human operator can make
the most use of motion cues for vehicle
dynamics which lead to significant roll

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motion above one radian per second.   Such
vehicle dynamics include low order dynamics
such as 1/s as opposed to $1/s^2$ and dynamics
with an associated high control stick gain.

It is possible, in some cases to use the
body of data obtained for this thesis to
predict actual in-flight or moving-base
measurements of the human operator's de-
scribing function from fixed-base measure-
ments of the human operator's describing
function.

RELATIVE EFFECTS OF ROLL AND YAW MOTION CUES
IN MANUAL CONTROL

P.B. Dinsdale

Master's Thesis

Department of Aeronautics and Atronautics
1968

ABSTRACT

Experiments were performed to determine the
relative contribution of otoliths and semi-
circular canals to manual control of difficult
(K/s^2) vehicle dynamics. Motion cues (yaw and
roll) were provided to subjects with head ori-
entations carefully specified such that in one
case the semicircular canals only were stimu-
lated, whereas in the second case, the otoliths
as well as the semicircular canals were stimu-
lated. Human operator describing functions
were measured and compared for the two cases.
High frequency human operator amplitude ratio
was greater when both otoliths and semicircular
canals were stimulated.

Further work in this area produced two papers, the abstracts

of which are given below:

MOTION CUES IN MAN-VEHICLE CONTROL: EFFECTS OF
ROLL MOTION CUES ON HUMAN OPERATOR'S BEHAVIOR
IN COMPENSATORY SYSTEMS WITH DISTURBANCE INPUTS

R.S. Shirley and L.R. Young

ABSTRACT

The human operator's use of roll-motion cues is
investigated for man-vehicle control in a comp-
ensatory tracking task with a disturbance input.
Extensive data for the human operator's describ-
ing function are taken for a wide range of vehicle
dynamics under conditions of visual cues only,
roll-motion cues only, and simultaneous visual
and roll-motion cues. Addition of roll-motion
cues to visual cues permits the human operator
to increase his phase lead at frequencies above
3 rad/sec. This allows him to increase the system
open-loop gain without a loss of system stability,
and thus to reduce the system tracking error.
Experimental results indicate that in a compen-
satory system with a disturbance input, any
condition in which additional human opertor lead
at frequencies above 3 rad/sec would be useful
is a condition in which roll-motion cues would
aid.

CONTRIBUTIONS OF ROLL AND YAW MOTION CUES IN
MANUAL CONTROL

L.R. Young and P.B. Dinsdale

ABSTRACT

Previous communications concerning the effects
of roll motion cues on pilot characteristics
emphasized the increase in low frequency gain
and the phase lead contributed at higher fre-
quencies. To determine the relative contri-
butions of semicircular canal and otolith
responses, experiments were performed in yaw
and roll control of a K/s^2 vehicle on a moving
base rotation simulator. Comparison of human

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operator describing functions shows that
rotation with respect to the g vector (roll)
leads to higher gain than rotation in a
horizontal plane, although no significant
difference in phase lag appears.

A different series of experiments investigated the
possibility of significantly extending the limits of manual
control of unstable vehicles by positioning a force control
stick with feedback of the state variables of the system.

The results of the experiment showed that positioning
a force stick with feedback from the controlled plant greatly
increased the controllability when displacement is fed back
from a first order plant and velocity is fed back from a
second order plant. Feeding back position of a second order
plant did not greatly improve the second order plant's
controllability.

This research is summarized in the Engineer's Thesis
of Phillip Noggle, abstracted below.

MANUAL CONTROL OF UNSTABLE VEHICLES USING
KINESTHETIC CUES

P.L. Noggle
Engineer's Thesis

Department of Aeronautics and Astronautics
1969

ABSTRACT

A control stick was constructed which sensed
the operator's force but moved only in res-
ponse to an external electrical signal,
driving the operator kinesthetic cues. First
and second order plants were used in experi-
ments which compared human operators' ability

to control instabilities with the force
sensing stick fixed, driven by plant posi-
tion, and driven by plant velocity. Great
improvement in human control capability
were found in controlling first order
plants with the stick driven by plant
position and in controlling second order
plants with the stick driven by plant
velocity. The large improvement was due
to a reduction in lead required of the
operator and a reduction in operator delay
time. The necessity for lead was reduced
by providing the operator with a signal
in the form of stick motion, with the
proper phase for stabilization. The delay
time was reduced by enabling the operator
to transmit the stabilizing signal to the
plant by stick reaction forces determined
by muscle tensing instead of voluntary
action.

A comprehensive overview of human control was prepared

by Professor Young.

HUMAN CONTROL CAPABILITIES

L.R. Young

From: Bioastronautics Data Book, 2nd Edition,
NASA SP-3006 (Parker and West, Editors) 1973.

ABSTRACT

This chapter concentrates on the capabilities
and limitations of man as an element in a
closed loop control system under normal en-
vironmental conditions. Only by careful
consideration of the engineering aspects of
man as a control element can perfor..ances
of man-vehicle systems be assessed, stability
and power assists be designed, and trade-offs
between manual and automatic functions be
determined objectively.

The human operator uses his various senses
to gain information on vehicle state and
the command situation, integrates this in-
formation centrally where the appropriate
control actions are decided upon, and through
use of effectors such as control sticks,

changes the inputs to the vehicle or plant
which is being controlled. In the typical
piloting application, man participates in
two levels of this man-machine system:
control and guidance. In his control func-
tion, man establishes an equilibrium state
of vehicle motion and regulates departures
of the vehicle from equilibrium. In guidance
man determines the appropriate course and
speed to reach a desired point under con-
sraints of time, fuel, position error, and
accelerations. Typically the progression
from control to guidance involves manual
control functions which are successively
slower in their characteristics but require
a higher level of decision-making. The
remainder of this chapter cnsiders the
human controller, controls and displays.
The effects of other-than-normal environ-
ments on the human senses and effectors
are discussed in other chapters of this
book.

1.2   NEUROMUSCULAR CONTROL

A study aimed at producing a new model of the muscle spindle in order to gain a fuller understanding of the control characteristics of the human neuromuscular system in tracking tasks.

Preliminary work evolved into three areas:

1.   Design and construction of an arm manipulator incorporating electric torque motor drive, force and position sensors.

2.   Design of the electric torque motor non-linear compensation to enable the torque motor to act as a position or torque transducer.

3.   Data processing and analysis design.

The objectives of the experiment were to determine first, the criteria by which control is allocated among the levels of neuromuscular control under various tracking conditions. Second, to develop a method to distinguish higher center responses and determine the logic of these responses. And finally to investigate the location of remnant response sources.

The maintenance of a fixed limb position in the face of a disturbance can be achieved through the interaction of

sensory information related to the disturbance and continuous fine adjustments of muscle tension required in the control of upper limb position. More fundamentally, it is assumed that these adjustements exemplify the operation of two feedback loops; one which is peripheral and the other central; this leads to the proposition that further insight into these feedback mechanisms can be gained by examining responses underlying the recovery from controlled disturbance of power.

The arm manipulator was designed and constructed and a series of experiments involving terminated ramp type input was performed. Preliminary conclusions were drawn from the analysis of force response to the terminated ramp position disturbance. The response to each size of terminated ramp may be regarded as indicative of the peripheral and central nervous system organization. Characteristics of the response to an arm disturbance include:

1. An early oscillatory force response has been observed and cited as a manifestation of three possible mechanisms.

   a. Inertial reaction force due to passively accelerating the forearm.

   b. A spinal reflex pattern elicited as bursts of muscle activity in synergistic muscle groups.

   c. Active muscle properties which are minimally influenced in this early response by afferent feedback.

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2. The maximum amplitude of this oscillation - termed the "reflex" force amplitude varies in a way consistent with regions of stiction, coulomb friction and viscous friction, and is identified as a change in the neuromuscular system gain with ramp velocity.

3. The "reflex" force oscillation period changes with velocity gain from 162 msec to an asymptotic value of 120 msec in a manner which is not consistent with a second order system damped natural frequency unless the spring constant of the system changes with velocity gain or damping ratio. Two physiological mechanisms by which the damping ratio and spring constant may be changed are first, the force versus velocity of shortening characteristic of active muscles, and second, a group Ia and group II muscle spindle afferent feedback to the alpha motoneuron mediated by the gamma dynamic motoneuron.

4. The minimum delay for the centrally initiated corrective force is 250 msec.

    A minimum of 4 repetitions of each stimulus size is necessary to deduce statistically significant conclusions between stimulus size.

Several experimental conditions were tried, with some form of sensory deprivation applied in each. Conditions used involved eyes closed (deprivation of visual cues) and a nerve block at the wrist (cutaneous feedback deprivation).

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This work was completed in 1973 and the results are incorporated in the thesis of John Allum which was completed in the summer of 1974. The abstract of this thesis is given below.

THE DYNAMIC RESPONSE OF THE HUMAN NEUROMUS-
CULAR SYSTEM FOR INTERNAL-EXTERNAL ROTATION
OF THE HUMERUS

J.H.J. Allum

Sc.D. Thesis

Department of Aeronautics and Astronautics

1974

ABSTRACT

Current neurophysiological literature reflects
some doubt concerning ways in which the neuro-
muscular system handles disturbances. The
experiments and results discussed here, focus
on an investigation of the control strategies
of the neuromuscular system at the human shoulder.
The test situation involved the use of a randomly
occurring limb displacement during the mainten-
ance of a bias force. Lateral forces recorded
at the hand as a result of the initial reaction
to, and subsequent correction of, a displacement
to the humeral rotatory posture may be divided
into four time segments. First, the force re-
sponse to viscoelastic properties of activated
muscle is observed. Approximately 100 msecs
after the displacement commences, a short latency
force response occurs. Subsequently, a long
latency force response, consistent with voluntary
motor reaction times, completes the correction
to the displacement. Some 500 msecs thereafter,
and dependent on the final steady state force
bias level, force tremor develops. Pre-displace-
ment bias force has been successfully employed
to modify all four segments of the response. The
bias force modifies both the visco-elastic res-
ponse and the short latency response as expected
from reported findings on decerebrate cats. The
stretch reflex increases with bias force.

Two other experimental conditions also modified

segments of the response. When the subject
closed his eyes prior to the disturbance,
the change in short latency force response
with each size of disturbance is more linear
than those responses obtained for eyes open
condition. Removal of cutaneous input from
the hand, by a total nerve block at the
wrist, drastically alters all four segments
of the response except for the visco-elastic
response.

The classical views of motor system load
regulation is that signals originating
from muscle spindles impinge directly
on alpha motoneurons of the same stretched
muscle to correct the disturbance. Current
literature expresses the view that segmental
reflexes require a pre-existing alpha-gamma
coactivation to operate (servo-assistance).
Another view is that muscle spindle signals
follow an indirect route through a servo-
assisted transcortical loop. These views
concerning important force responses are
questioned in this thesis.

No force changes consistent with monosynaptic
reflexes are observed. Even the exceptionally
strong short latency force response observed
in some subjects comprised only 15% of the
total force response.

Thre results indicate that the visco-elastic
properties of muscle and a preprogrammed
voluntary response are the most important
factors in load regulation. The short latency
response is viewed as a possible test signal
which informs the central nervous system of
a load change and thus aids in the selection
of an appropriate preprogrammed response.

There are two views of the cause of physiolog-
ical tremor. One is that the cause is predom-
inantly mechanical; an interaction between the
load on the muscle and the activated visco -
elastic properties. The alternative is a
cause of neural origin possibly in the muscle
spindle segmental reflex. In an examination of
post response physiological tremor for each of
the experimental conditions, it is concluded
that physiological tremor is neural in origin.

The major journal article on this research appeared in Experimental Brain Research in 1975.

RESPONSES TO LOAD DISTURBANCES IN HUMAN SHOULDER MUSCLES: THE HYPOTHESIS THAT ONE COMPONENT IS A PULSE TEST INFORMATION SIGNAL

John H.J. Allum

ABSTRACT

Human motor control has been investigated by applying displacements acting to rotate the shoulder while the subject was endeavoring to maintain a constant position against a pre-existing force delivered by a system of finite stiffness. Four separate stages of the force response were distinguished. First, for the initial 100 msec, an increase in force which was attributed to the visco-elastic properites of activated muscle. Second, after approximately 100 msec, a "medium latency" increase in force accompanied by an increase in EMG activity. Third, a "long latency" increase in force consistent with voluntary action restored the arm to its original position. Fourth, some 500 msec thereafter and dependent upon the final steady state force level, a tremor might develop. No changes of force were seen that were of sufficiently short latency to be attributed to either Ia monosynaptic action or immediately following (within 15 msec) polysynaptic action of muscle mechano-receptors. Even the "medium latency" response was too weak to make an appreciable contribution to restoring the arm to its original position; at the best it provided only 15% of the force required. This response is often considered as a "stretch reflex" responsible for maintaining posture in its own right; for example, by means of a servo-assisted transcortical loop. Instead, it is now suggested that it might be a test signal designed to inform the central nervous system of the current loading on the muscle and thus permit the CNS to select an appropriate pre-programmed response from its repertoire of motor actions.

An additional article concerning the methodology, "The relaxed oscillation technique for the determination of the moment of inertia of limb segments" is currently in press and is abstracted below.

THE RELAXED OSCILLATION TECHNIQUE FOR THE
DETERMINATION OF THE MOMENT OF INERTIA OF
LIMB SEGMENTS

J.H.J. Allum & L.R. Young

ABSTRACT

Neuromuscular reflex forces are overwhelmed
by inertial reaction forces when a limb is
suddenly dispalced. A method, using forced
sinusoidal oscillations of the limb when the
limb musculature is relaxed, is described
for determination of the moment of inertia
of the limb. The slope of the graph of
peak to peak acceleration for each of a
series of oscillation frequencies (peak
velocity maintained constant) yields an
accurate measurement of the moment of inertia.
When the moment of inertia is multiplied by
the displacement acceleration and the result
subtracted from the corresponding force record,
neuromuscular reflex forces, and the visco-
elastic properties of activated muscle may
be observed.

1.3   HUMAN OPERATOR MODELLING

Considerable effort was spent in developing a learning model to describe the states of control laws a human operator passes through in learning a single relatively simple control

task. A Markov model describing states of knowledge of the system was constructed with the learning model described by Markov transition probabilities. Two theses were written based on this work. Their abstracts are given below:

A THEORY AND MODEL OF HUMAN LEARNING BEHAVIOR IN A MANUAL CONTROL TASK

A.E. Preyss

Sc.D. Thesis

Department of Aeronautics and Astronautics

1967

ABSTRACT

A theory is presented for the explanation of human learning behavior in a manual control task. In the performance of a psychomotor task, a human operator responds to sensory stimuli with limb movements. This complex psychophysiological phenomenon is conceptualized as a single channel information processing system. Transmission and processing of information take time, and the delay between the reception of a sensory stimulus and the execution of a motor response is treated as a finite sum of component times which are assumed to be statistically independent variables.

In the decision center, responses are selected from a set of possible control policies. Stored in memory are apriori estimates of the probability that a specific policy should be in force at the moment of decision. Policy selection

is determined by a rule which takes the
priors into account. Learning is effected
by a revision of the priors based on a
weighting of certain evidence. Baye's
theorem is the revision rule. Simple
and readily perceived events in the state
history of a dynamic process being con-
trolled are used for evidence in resolving
control policy uncertainty.

A model of human learning behavior is the
computer program obtained from a transla-
tion of the theory into machine language.
Behavior of the model depends not only on
the rules of information processing post-
ulated by the theory, but also on the set
of parameters characterizing the mental
and physical attributes of an individual.
Model behavior is compared with subject
behavior observed in a motor skill exper-
iment performed at M.I.T.'s Man Vehicle
Laboratory.

As set forth, the theory explains how a
human operator learns to regulate the
state of a dynamic process using a relay
controller. Generalization of the theory
to other task contexts is discussed.

This work was extended by T.T. Chien, in his Master's

Thesis which demonstrated the validity of the model when

applied to control of harmonic oscillators and unstable

processes.

HUMAN LEARNING BEHAVIOR IN MANUAL CONTROL TASKS

T.T. Chien

Master's Thesis

Department of Aeronautics and Astronautics

1967

ABSTRACT

In this thesis, applications of a stochastic model of human learning behavior to harmonic oscillators and unstable dynamic processes are verified. Experiments are performed to compare model learning behavior with subject learning behavior in manual control tasks. A modified model in the form of a computer program is presented in the light of the experimental and analytical results.

The main conclusions of this thesis are the following:

1. Verification of the theory of the basic model for explanation of human learning behavior in application to the dynamic processes of harmonic oscillators and unstable plants.

2. A single revision rule based on the double integration process for estimating posterior probabilities can be applied to all dynamic processes experimented.

3. The reaction time delay between the reception of a visual stimulus and the execution of a motor response has a significant effect upon the state history of the high speed dynamic processes being controlled. This effect should be taken into account in evaluation of weighting of evidence in resolving control policy uncertainty.

4. Both subjects and model can learn to contol the multiswitching optimal dynamic system in a sub-optimal way.

A series of presentations on this subject by Dr. Meiry were made in 1968. These included a paper presented at the Fourth NASA University Conference on Manual Control, held at the University of Michigan.

STOCHASTIC MODELLING OF HUMAN LEARNING BEHAVIOR

A.E. Preyss and J.L. Meiry

ABSTRACT

The application of a stochastic model of human
learning behavior in manual control tasks is
extended to the performance of the human
operator in regulating all second order dynamic
processes. In particular, the human control
decisions for optimal multiswitch and unstable
dynamic systems are found to correlate well with
responses recorded by the model in the study of
simulated subjects. The universality of the
model is discussed in the light of a series of
compensatory task experiments.

A second paper was prepared for the IFAC Symposium on Tech-

nical and Biological Problems in Cybernetics , Yerevan,

Armenia.

SKILL ORGANIZATION AND LEARNING BEHAVIOR

J.L. Meiry

ABSTRACT

A theory and model of motor skills learning
postulate a statistical decision process for
the human operator controlling a dynamic system.

The selection of response alternatives and the
revision of preferences for them are functions
of a decision center in the human mind. This

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decision center is one component of a hypothetic
single channel information system. Also included
in this information processing center are a sensor
which perceives the information upon which the
decision center acts, and an effector, which
executes the response decisions made by the center.

The model of human learning behavior is a digital
computer program which is obtained from a trans-
lation of the theory into machine language. Behav-
ior of this model is compared with subject behavior
in a controlled series of motor skill experiments.
The extent of the model's characterization of the
time-varying random nature of human learning is
brought out by this comparison.

1.3.1 Self Organizing Systems

Self organizing systems are systems which change their

structure when the input or plant changes under the conditions

where the controller has never experienced this change (this

latter is in contrast to self-adaptive systems). Some of the

important properties of these systems are involved with the

concept of its hierarchy. P.B. Mirchandani began investigations

in this area, considering at first the concept of multi-level

performance indices and coordinability. At each level of the

controller hierarchy a performance index is available which

dominates the lower level performance indices. Coordination

is defined as the decision problem of a control unit embedded

in the self-organizing system. A system is said to be coordinable

if the lower level control problem can be influenced so that

the overall objective is achieved. More simply, a two level

system is coordinable if the satisfaction of the sub-goal (lower

level performance index maximized) also satisfies the primary

goal (higher level performance index). Whereas modern control theory goes from the specification of a desired performance index to the automatic generation of control laws, the next step in hierarchical control systems is the specification of a "generalized utility function". The utility defines a hypersurface in state space. The performance index at any time, and hence, the control is obtained from the criterion of maximizing utility. Mirchandani has explored notions of partitioning the utility function and using the concept of "independent attributes". The relative importance of various elements in maximizing utility is determined by the utility gradient. Thus the use of utility functions enables the designer in principle to specify what he thinks is important about the system performance at any given time and have the performance index be determined automatically.

Applications of this theory to the human operator are of potentially great importance. Most of the existing human operator models consider the operator as a stationary system and this makes possible linear representations. However, separate models are required for different control tasks and different inputs. These models do not take into account any fundamental invariance of the human operator. Recent models of the human operator improved the state of the art by postulating the human operator as an optimal controller. Performance indices were obtained by trial and error until the model output matched the operator output. Separate performance indices were obtained for different systems. Still the

In the proposed theory, we postulated that the human operator had a generalized utility function, with an a priori probability of where he is on the hypersurface. We can accommodate the hypothesis testing mode by including the "hypothesis" as one of the coordinates in the utility space. The human operator would start at a certain state on this hypersurface and use that control which maximizes his utility over time. We postulated that the process of learning is the updating of the subjective probabilities as to where he is on the utility surface. This would imply that:

1. In a completely deterministic situation, with full knowledge of the system and the state of the system, a fully learned and highly motivated operator would give consistent responses.

2. In a situation where the plant is known completely, but the knowledge of the state is stochastic, the fully learned and motivated operator would give stochastically consistent responses.

3. In a situation where the plant is unknown and the state of the system is stochastic, the operator will show learning behavior until the knowledge of the plant is known, and then the operator would give stochastically consistent results.

4. In a situation where the plant is a stochastic system, the operator will show learning behavior until the knowledge of the probabilistic behavior of the plant is nearly equivalent to the real behavior, and then the operator would give stochastically consistent results.

If the task of the human operator is always the same, for example, to bring the state of the system to a null position, then we could note that the utility function (as a function of state only) is always the same regardless of the type of plant. We may thus be able to work with one less coordinate, i.e. the coordinate of hypothesis.

1.4 APPLICATIONS OF MANUAL CONTROL

A number of vehicle control applications problems were studied in the Laboratory, all of which bring out some particularly interesting aspect of the operator's control, and were intended to tie in with the more basic research performed on the biological subsystems and human operator models. A significant effort was devoted to the manual control problems associated with VTOL hovering, manual control of an elastic booster, ability to recover from disturbances in blind aircraft landings, EVA stabilization and control, and some ground transportation vehicles.

1.4.1 Automatic Landings

The proposal of automatic blind landing systems for commercial air transportation raised the question of the appropriate role of the pilot during the landing phase. In particular, the question of pilot adaptability in terms of back-up or takeover in the event of system malfunction must

be considered along with his ability to put in appropriate
control responses to land the aircraft in zero/zero weather
entirely on instrument information. Among the areas inves-
tigated were the importance of motion cues in detecting
malfunctions, the ability of the pilot to take over at any
phase of the landing and his ability to perform instrument
landings starting from a variety of initial conditions.

HUMAN ROLE IN THE CONTROL LOOP OF THE AUTOMATIC
LANDING AIRCRAFT

V.O. Vuorikari

Master's Thesis

Department of Aeronautics and Astronautics
1965

ABSTRACT

The object of this thesis is to study what kind
of information the pilot can obtain from three
different kinds of windshield displays during
automatic approaches and landings, and if he is
able to detect the possible malfunctions in the
automatic system from his display. In the study,
an airplane landing was simulated by using an
analog computerand two degree of freedom moving
base simulator. The picture of the runway
projected to the pilot was the only visual in-
formation source in the cockpit.

The tests were performed by feeding step and ramp
disturbances into roll rate or pitch rate inte-
grators in the analog computer, and the roll, yaw
and pitch response times were calculated from the
recordings.

It can be seen that for roll control only the
most simple picture of the runway, two lines
representing the runway boundary lines, are
enough in most cases, but the yaw control
lacks accuracy and damping in this case. Adding
the horizon to this picture improves a little
the yaw control by allowing the pilot to add
yaw rate feedback to his control.

The pilot was not able to obtain enough infor-
mation from these two simplified pictures of
thr runway to control the longitudinal axes and
several crash landings were recorded during this
part of the testing.

The flight path marker provided enough infor-
mation to the pilot for controlling also the
longitudinal axis and the response time to
moderate pitch rate disturbances was less than
half the time of response without the flight
path marker. No crashes were recorded when
the flight path marker was used.

In the tests, both moving-base and fixed-base
simulations were made, and it was found that
the fixed-base lateral response times were
about twice as long as the respective moving-
base values.

1.4.2 Helicopter Control

The control of the completely unstabilized helicopter

is normally beyond the ability of the human controller, and

consequently a number of passive or active stabilization loops

are built into the vehicle. Since the vehicle is inherently

a high order controlled element, it made an interesting

amplification of our hypothesis on the role of the vestibular

system in control of high order systems. A systematic invest-

igation was done on helicopter handling qualities, including

the requirements on display, external stabilization, and the

importance of motion cues.

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VISUAL AND MOTION CUES IN HELICOPTER FLIGHT

P. Benjamin

Master's Thesis

Department of Aeronautics and Astronautics
1966

ABSTRACT

This thesis investigates the relative importance of
motion and visual cues on the ability of experienced
pilots and non-flying subjects to control a hovering
helicopter. It examines the interaction of three
different forms of input information and the methods
by which they are utilized by these two classes of
subjects. The method by which control of such a high-
order system as a helicopter is effected is discussed
and a theory on this is advanced. A simple visual
display system which provides a unique description of
position and attitude with respect to a defined axis
system and utilizes relatively inexpensive and avail-
able analog equipment is presented.

Another approach to the multi-loop manual control problem

was one which assumed a cascade model for the operator. The use

of average transient responses to ramp inputs as a rapid indenti-

fication technique facilitated the study of the situation.

HELICOPTER CONTROL: A MULTILOOP MANUAL CONTROL
SYSTEM

G.R. Friedman

Master's Thesis

Department of Aeronautics and Astronautics
1967

ABSTRACT

The human operator's performance in a higher order
multi-loop task, typified by the helicopter, is
studied using the method of average responses.
This method permits a time domain, transient input

analysis. A cascade model configuration for the
human operator is proposed. In this configuration,
the first human operator model controls attitude.
This model is identical to that of the single-loop
model for the same dynamics and consists of a lead
time constant of 5 seconds, a neuromuscular lag of
0.1 second, and a pure time delay of 0.28 seconds.
The attitude reference for the attitude control
loop is provided by a second cascade human operator
model consisting of a one second lead operating on
the position error. A general programming system
for average response experiments, using the GPS
290T Hybrid Computer is described.

1.4.3 Flexible Booster Control

Control of a flexible booster vehicle by a man is a

challenging task since the rigid body dynamics are unstable

in the aerodynamic region and the higher frequency elastic

modes tend to interfere with his ability to maintain stable

control. A fixed and moving base simulation of control of a

flexible booster was done to establish the effects of the high

and low frequency motion cues, the interaction between elastic

mode amplitude and ferquency and the ability to control the

rigid body mode, and the duplication of control operator

limitations in terms of display requirements and automatic

stabilization necessary. The work on booster control was

carried out by P.S. Kilpatrick and is summarized in his Master's

thesis which is abstracted here.

BENDING MODE ACCELERATION INFLUENCE ON PILOT
CONTROL OF FLEXIBLE BOOSTER DYNAMICS

P.S. Kilpatrick

Master's Thesis

Department of Aeronautics and Astronautics
1965

ABSTRACT

This investigation is concerned with the general
problem of man's ability to directly control a
large flexible launch vehicle. Specifically, the
effect of a flexible body mode on pilot control
of simulated single axis Saturn V rigid body
dynamics is studied. First bending mode ampli-
tude and natural frequency, and the type of simu-
lation, fixed or moving base, are the variables
considered most intensively. Brief studies of
variations in the RMS level of the disturbance
signal and comparisons of two proposed control
stick filters and vehicle augmentation schemes
are included.

The effects of the flexible mode on the pilot and
his closed loop performance are analyzed by ratios
of attitude error to disturbance signal and control
stick output to attitude error, and by computed
pilot transfer functions.

Results show that a pilot's ability to generate
lead compensation and to control the attitude
error decreased as the bending mode amplitude
increased. Significant deterioration occurred
at the lowest bending mode amplitude, 1/3 the
value at the proposed location of the Saturn V
attitude gyro, under study. The pilots' gain
and ability to control the attitude error de-
creased during the moving base experiments.
This result is attributed to dynamics and non-
linearities associated with the simulator, a
less sensitive moving base display, and possibly
vestibular uncertainty and insensitivity con-
cerning small deflections from the vertical. With
increasing bending mode amplitude, pilot performance

deteriorates at approximately the same rate for both

$$\omega_{nbd} = 5 \text{ and } 7 \text{ rad/sec} \quad .$$

However, for a given amplitude, the 5 rad/sec bending mdoe generates only one-half the acceleration of the 7 rad/sec bending mode.

1.4.4 Stabilized Motorbike

As a test vehicle in which visual and motion cues are used for dynamic orientation, we instrumented a motorbike. We measured tilt angle from the apparent vertical and steering deflection to identify the rider's control function, and also developed automatic stabilization to attempt to duplicate the rider's performance. This work is summarized in the thesis abstracted below.

A RATE GYRO AUTOPILOT FOR A
MOTORBIKE

L.M. Nashner

Master's Thesis

Department of Aeronautics and Astronautics

1967

ABSTRACT

The object of this thesis is to develop an autopilot which maintains the roll stability of a motorbike and guides it on a course commanded by a passive rider on the motorbike. The single control parameter of the autopilot is the steering wheel angle. The feedback sensor is chosen to give dynamic information closely related to that which is available to the human rider, the sensory outputs of the vestibular system.

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The two most appropriate sensors, the pendulum and the gyro, are initially considered in simplified linear studies. The rate gyro is found to give superior performance and is chosen as the feedback sensor.

The autopilot configuration is first simulated on an analog computer to accurately determine the requirements of the drive, the feedback compensation and the loop gain. The actual hardware is assembled to conform to the specifications of the simulated autopilot.

The autopiloted motorbike has a well damped response to step torque disturbances resulting in lean angles of up to 30 degrees. The response limitation of the autopilot is primarily due to its nonadaptive loop gain. While a single feedback compensation for all speeds is used, a specific setting of feedback gain limits the range of bike speeds for which the autopilot is stable to a small region.

The autopiloted motorbike is found to be directionally unstable when it is commanded to maintain a straight course. Analysis shows that considerable improvement in the accuracy and elimination of drift in the roll angle sensor will not increase the directional stability significantly. Feedback information of the lateral error of the bike on its track is necessary if the system is to maintain a straight course within a 15 meter tolerance for distances over 200 meters.

The problem of manual control of a motor bike, motorcycle or narrow passenger vehicle is of unusual interest for two reasons. First, the multi-loop control required of the human is brought out quite clearly, and his ability to use motion cues to stabilize the inner loop may be investigated. Secondly, aside from his steering commands, the human is closely coupled to the vehicle control by means of his weight shift and the resulting structural resonance as the mass of his body shifts with respect to the vehicle frame. Many of these problems are discussed in a paper by Professor Li abstracted below.

STABILITY AND CONTROLLABILITY OF VEHICLES FOR
HIGH SPEED AND HIGH TRAFFIC PERMEABILITY

Y.T. Li

ABSTRACT

A general study of the basic requirements of
vehicles for individual and public transport-
ation systems leads to the belief that the
incorporation of an active suspension system
into the vehicle would constitute a major step
forward. Various aspects of an active suspen-
sion system were scrutinized. Favorable results
from an experimental test vehicle confirmed that
belief. By incorporating the principle of an
active suspension system, a narrow vehicle was
proposed for commuter traffic; a utility vehicle
for agriculture and military application; and a
monorail vehicle for public transportation as
well as for super high speed intercity trans-
portation.

1.4.5 Spacecraft Navigation

A study was carried out on the problems associated with

the performance of a precise navigation task such as that

which would be performed on the Apollo voyages.

HUMAN PERFORMANCE DURING A SIMULATED
APOLLO MIDCOURSE NAVIGATION SIGHTING

C.M. Duke and M.S. Jones

Master's Thesis

Department of Aeronautics and Astronautics

1964

ABSTRACT

This is an investigation into the effects of
certain variables on the performance of man
doing a precise superposition task. This

simulates the task that the project Apollo
navigator will be required to perform during
the mid-course (translunar and transearth)
phases of the proposed lunar excursion. For
this purpose, the Apollo sextant simulator
located at the MIT Instrumentation Laboratory
was used. The variables were (1) rate of
spacecraft motion (2) magnification of sex-
tant telescope (3) orientation of landmark,
and (4) star-landmark contrast ratio. In
order to determine the effect of each vari-
able independently, only one was varied at
a time.

Three subjects were used. Each performed
the superposition task by using a set of
hand controllers until the star was on top
of the landmark as seen through the sextant
telescope. At this point the subject pressed
a "MARK" button, which recorded the error
that he made in seconds of arc. For each
given set of conditions, the subject per-
formed the task 25 to 30 times. For each
such series, the mean error was computed
(absolute mean distance from perfect super-
position). Statistical tests were then
applied to these means to check for signi-
ficant changes in error due to changing one
of the variables.

Results indicate that two of the four vari-
ables investigated have a statistically
significant effect on the accuracy. The
errors increase with faster craft motion,
and at the higher rates more fuel must be
expended to keep the landmark in the sex-
tant's field of view. A greater magnifi-
cation results in overall smaller errors,
but more investigation should be done to
determine if they are enough · smaller to
warrent heavy or more expensive equipment.
Orientation of the landmark seemingly had
no effect on the accuracy of the super-
position task. However, orientation may
have an effect on landmark recognition,
and this should be kept in mind during
navigator training. The contrasts studied
indicate that so long as both the star and
the landmark are lighted sufficiently to
be recognizable, the errors will be essen-
tially the same at any overall brightness
level, with one exception. The exception

is that a very bright star on a dim background
seemingly increases the error. More studies
should be made in this area to determine a
maximum star brightness for acceptable error.

Interestingly, one of the students performing this work (Charles

Duke) later had the opportunity to test his predictions as an

Apollo astronaut who landed on the moon.

1.4.6 EVA Stabilization

Studies were undertaken on a new concept for attitude

stabilization and control of an astronaut outside of his space

vehicle. The problem of attitude stabilization is of prime

importance for an astronaut during extravehicular operations.

Most of the existing systems require the use of one or both

hands, a serious inconvenience if one is engaged in precise

manual work. An alternate controller would involve the use

of natural motions of the head for controlling attitude change.

Some of the necessary constraints which would have to be placed

on such a system include: the use of the head for control

purposes should not interfere with visual functions; the head

should be free to move naturally along any axis; instrumentation

on the head itself should be avoided or minimized; and some lock

out device should be provided for those times when head motions

are not for the purpose of attitude change.

Experiments were run to determine the feasibility of

using the astronaut's head motion as an actuator for a portable

attitude control system. This concept stemmed from our work on

the human vestibular system and space orientation in which it is clear that all the postural control loops act to stabilize the head and body in space. Thus a system which would drive the astronaut's trunk to a given position with respect to his head should be quite satisfactory. The astronaut could command a turn by turning his head in the desired direction.

Two approaches were considered. The first relies on the voluntary muscle contractions in the neck corresponding to head movement. Muscle activity detected by surface electrodes yields an EMG of the type used in prosthetic devices to achieve more natural input response characteristics for an amputee. The principle problem with this approach are the separation of neck muscle recordings into roughly uncoupled pairs and the choice of the control mode among proportional, rate or some combination of these. The second approach is the direct measurement of the head movement with respect to the neck using potentiometers or resolvers linked to the helmet. This system is obviously feasible but would have the disadvantage of requiring additional hardware and would be encumbering.

The results of the first approach are reported in the Master's Thesis of L.C. Von Renner.

EXTRAVEHICULAR ATTITUDE CONTROL BY USE OF HEAD
MOTIONS

L.C. Von Renner

Master's Thesis

Department of Aeronautics and Astronautics

1970

ABSTRACT

On the basis of a survey conducted on existing
techniques for astronaut extravehicular attitude
control in space, experiments were performed to
determine the usefulness of bioelectric currents
generated in muscle tissue as a control signal
source.

Muscle sites were identified on the neck and bio-
currents (electromyographic signals or EMGs) were
detected using surface electrodes. Raw signals
were generated by turning the head right or left
with respect to the body; subsequent conditioning
was performed using a hybrid computer. Motion
cues (yaw) were provided by a rotating chair which
a subject attempted to control by moving his head.
Performance levels based upon integrated squared
error were compared for two separate plant dynamics
between EMG and conventional pencil-stick control.

Examination of the data revealed that control of
yaw attitude using EMGs was a practical means of
providing hands-off control. However, EMG perfor-
mance was in all cases poorer than equivalent tests
conducted using a stick. This probably resulted
from the large deadband (approximately 45 degrees
normally) which existed in the physical angle of
turn required of the head to produce a measurable
signal. Recommendations are made for describing
function analysis of the data and the investigation
of other mechanical methods for using the head
position as a control signal source.

An alternate solution to the problem is to modify the

existing space helmet to incorporate features which will allow

for the use of head movements as an attitude control mechanism.

If the head is to be used to indicate attitude changes,

some system capable of detecting head movements is necessary.

An electro-optical system utilizing gallium Light Emitting Diodes

(LEDs) and photodetectors, mounted on the inside of the helmet,

was designed and tested for human operator single axis control.

Preliminary experiments were performed to evaluate the efficacy of the decoupling scheme which had been worked out. The vehicle considered is the three axis LINK GAT-1 of the Man-Vehicle Laboratory. The preliminary experiments utilized the yaw dynamics only. In all of the cases, the system proved to work correctly and the decoupling showed good results. No significant differences were observed between the three axes.

In the actual experiments, both the performance of the head control and conventional stick control were compared for each separate axis in the case of compensatory tracking tasks. The ability to control the vehicle was tested for the cases of pseudorandom input disturbances. Two random functions (high and low frequency) were available, each having zero mean. Each trainer axis was tested separately. While one motion was being studied, the other two axes were locked out by position control. One avoided therefore, any possible bias on the target caused by mechanical drift of these unused axes.

Roll was the weak point in head control, however, excluding the roll axis, the head motion control performed extremely well. A strong point of the method is, of course, the naturalness associated with the head movements. No subject complained of visual interference and they generally felt that the task of head control was easier. It is probable that hand motions are more precise than head motions, especially when the error to

be compensated becomes small. However, no definite conclusions could be reached before testing both systems in the three axis situation.

Precision, speed, stability, smoothness and naturalness of both manual and head piloting were compared in the three axis situation. Four targets were established on the screen in such a way that, to be reached, each of them required the use of the three degrees of freedom of the trainer. The pilots were required to minimize the traveling time between their destinations on the screen. Furthermore, they had to stabilize their position on the target for at least 15 seconds. Stability was estimated visually by the experimenter and clearance to leave for the next target was radioed to the pilot when the result was judged satisfactory.

Head control led to simultaneous motion on the three axes. By looking in the right direction, the subject was taking the shortest path from one target to the next. As he kept his head aimed at his destination, the position error between head and helmet gradually decreased following the trainer motion. A few corrections were then made in the vicinity of the target to lock into the required position. Starting from one spot and locking into another generally required ten to fifteen seconds. No significant difference was noted between subjects and all of them were able to stabilize on the target for the required time without any problem.

With the stick, however, the motions were clearly

sequential. Knowing their destination, the subjects

generally estimated which axis required the largest dis-

placement and started motioning on that particular axis

first. A new estimation was then made, followed by

another decoupled move, and so on. This behavior resulted

in a longer pass between each target, but the total amount

of time spent travelling and stabilizing was about the

same as for head control.

These experiments are summarized in the Master's

Thesis of Bernard Chouet, abstracted below.

AN ELECTRO-OPTICAL ATTITUDE CONTROL SYSTEM
FOR ASTRONAUT SPACE ACTIVITIES

B.A. Chouet

Master's Thesis

Department of Aeronautics and Astronautics
1972

ABSTRACT

The possibility of using head motion as a
natural way of stabilizing and controlling
one's attitude in a zero-g situation has
been investigated. An electro-optical
monitoring system was built for the detec-
tion of such motion. Design factors such
as reliability, flexibility, maintainability
and linearity were among the main consider-
ations for the elaboration of the system.

Monitoring is achieved through an arrangement
of silicon photodetectors fitted in the hel-
met wall. Two Light Emitting Diodes (LEDs)
attached to the pilot's helmet liner, provide
the AC modulated radiation in the near-
infrared region within a narrow spectrum
centered at a wavelenght of 0.93 μ. Pitch

and roll motions of the head are detected by
a set of two detectors for each axis. Direc-
tion of motion is given throgh electrical
phase opposition of the detector set. Yaw
has a similar arrangement. However, for this
axis, a back up of two extra sensors is pro-
vided to insure a monitor output saturation
level when the pilot is performing large
motions. Dictated by the helmet geometry,
the limits of rotation are ±20° in the pitch
and roll axes. On the yaw axis, the monitor-
ing range is bounded at ±60°. Beyond these
limits the monitor output voltage decreases
with an average slope of 0.5 volt/degree of
rotation.

Electromagnetic shielding has been investi-
gated and it was found that it can easily
be provided by means of a vacuum deposit of
a thin layer (500 Å) of aluminum or gold
inside the helmet.

Feasibility of the Attitude Control System
(ACS) was demonstrated for each axis for
compensatory tracking tasks. Two sets of
experiments were performed, one using a
two-dimensional display configuration, the
other with the three-axis motion simulator
of the Man-Vehicle Laboratory. The monitor
outputs were decoupled with an on-line PDP-8
digital computer. Two pseudo-random signals
of bandwidths 0.155 Hz and 1.55 Hz provided
the disturbance inputs to the plants consid-
ered in the experiments.

Compared to the conventional Stick Control,
the performance of the Head Control is sur-
prisingly good. In a three-axis situation,
Head Control proved to be more natural as
it requires less attention from the pilot
than Stick Control.

Describing functions were obtained for
comparison of the dynamics of both controls.

A paper on this subject was published in 1974.

TRACKING WITH HEAD POSITION USING AN ELECTRO-OPTICAL MONITOR

B.A. Chouet and L.R. Young

ABSTRACT

An electrooptical head-position monitoring system was designed and built and is used in single-axis and three-axis "hands-off" control tasks. The monitor consists of a transparent plexiglass body-fixed helmet provided with a set of eight silicon photo-detectors sensing pitch, roll, and yaw motions of the head. Two light-emitting diodes, attached to the pilot's helmet liner, provide the AC modulated near infra-red radiation. Head control is compared with conventional manual control for single-axis and three-axis tracking tasks. Both performance curves and describing functions are presented.

II

DISPLAYS

2.1   THREE DIMENSIONAL DISPLAYS

In 1966, the Laboratory began work on the development of a hybrid computer generated contact analog visual display in which various perceptual "depth cues" are included on a two dimensional CRT screen. This display format was chosen for several reasons: with the increasing complexity of modern V/STOL aircraft, helicopters, under sea vehicles and spacecraft, and the precision maneuvering requirement which is being placed upon them, there is clearly a need for more advanced display systems than were currently available at that time. The displays should convey information, in an integrated and visually compelling fashion, about the vehicle's position and orientation in space.

The concept of the incorportation of multiple depth cues in contact analog displays was certainly not new. The term "contact" implies that the pilot will be presented with a display that appears to be, insofar as possible, a view of the real world as seen from the cockpit while flying VFR and navigating out the window.

It was felt that, regardless of the requirements for direct parameter readout, the basis for more advanced

display systems would be a truly realistic contact analog

display; one which is truly integrated and visually compel-

ling. Incorporation of third dimension information into

the display in a realistic way is essential.

The most straightforward way of including three dim-

ensional information in a display is to create a stereo-

scopic view. Several techniques are available to do this,

but all of them have disadvantages which make them impract-

ical. Stereopsis may be created with polaroid viewers

and head mounted TV techniques, but aside from interfering

with the normal visual field, they involve considerable

objectionable encumbrance of the pilot's head. Holographic

display techniques, while making rapid advances, have not

yet been developed to the stage where they may be considered

practical for on-line general displays.

Consequently, it was decided that the most useful

area of investigation, given these constraints, would be

to examine the possibility of including other "depth cues"

in a display with a two dimensional format.

2.1.1 Depth Cues

It has long been known that stereopsis (the psycho-

physical perception of depth associated with binocular vision)

and the related clarity of the image on the retina (depth of

focus) are not the only means which a vehicle pilot employs to obtain depth information from his normal visual field. Some of the known effects may be identified as follows:

1. "Deflection" cues, due to

   a. Scene rotation and translation

   b. Observer rotation and translation

   c. Movement parallax between objects in the visual field.

2. "Non-deflection" cues, due to

   a. Inverse square law of illuminance

   b. Aerial perspective (loss of image clarity due to intervening air mass)

   c. Linear perspective

   d. Interposition effects (where closer opaque portions of a scene hide more distant points located behind them in the visual field).

Rotation and translation of a simple two dimensional perspective representation of a three dimensional scene (such as in the shadow cast on a screen by a moving three dimensional object) is well documented. It seemed likely that head motion would provide as powerful a cue at closer ranges. In an attempt to make an assessment of head motion as a depth cue, experiments were performed with different size cubes and spheres held motionless in a dark room. It was verified that:

1. Binocular vision (stereopsis) provides a very strong depth cue; but

2. Monocular vision with head movement gives a depth cue which is almost as compelling as binocular vision.

3. If no deflection cues are present, monocular vision with the absence of observer head movement gives a poor depth cue.

These experiments were performed with fluorescent objects illuminated with UV light and no more than 15 feet away from the observer. Conclusions are that head movement provides a strong depth cue for an object being viewed at close range.

On the basis of these preliminary experiments, it seemed useful to investigate the possibility of building a visually compelling "three dimensional" contact analog display system in which the non-stereoscopic deflection and non-deflection cues alone were incorporated.

The apparatus developed consisted of a computer generated CRT display of a cube, presented in perspective with inverse square law intensification. The cube appears as a solid object, as all lines leading to hidden vertices are blanked. The display operates continuously, showing the "updated" scene thirty two times per second. The pilot has full six degree of freedom control over the scene through simulated vehicle dynamics. Ultimately, an ultrasonic head position monitor was used to track the pilot's head motion,

and the computer used this information to produce the proper change in aspect and screen parallax to make it appear to the observer that he can "look around" the cube. On the basis of the pilot's control inputs, the analog computer determines how the hypothetical vehicle would move and feeds this information to a program which keeps track of all the points in the visual field which are to be displayed. The computer performs rotations and translations on this field in three dimensional body coordinates to account for the motion of the vehicle. This digital program also calculates, on the basis of the current three dimensional field, what the field would look like if seen through the display "window" from the pilot's current head position, and prepares a two dimensional display which fits these requirements.

Since the display was to be used exclusively for experimental purposes, a cube seemed to be the ideal object to display, because of its simple, linear shape and its symmetry, which could be exploited.

This work led to a Master's Thesis by Robert M. Vircks, the abstract of which is presented below:

INVESTIGATION OF HEAD MOVEMENT AND INTENSITY
AS DEPTH CUES IN A PERSPECTIVE CONTACT ANALOG
DISPLAY

R.M. Vircks

Master's Thesis

Department of Aeronautics and Astronautics
1968

ABSTRACT

To determine the depth cue value of head
movement perspective, and image intensity
as a function of depth, an experimental
investigation was conducted.

A contact analog 3-D display system was
programmed on a hybrid computer. A line
drawing of a single cube fixed in space
was displayed on a cRT screen as if the
screen were a window. This was accom-
plished by using the equations of linear
persepctive for a monocular observer
whose head position is variable with
respect to the screen. Motions of the
vehicle, containing the observer and the
screen, were simulated using the six
velocities in body fixed axes.

An experiment was conducted to determine
the amplitude of a sinusoidal voltage
applied to the CRT intensity grid as a
fucntion of line length, so that lines
drawn in constant time intervals would
have an apparent brightness independent
of line length.

Depth discrimination experiments were con-
ducted using the perspective display with
combinations of head movement and cube
intensity as a function of depth. The
cube was displayed as if it were at one of
a set of discrete depths and the subject
asked to identify that depth. The result-
ing stimulus-response matrices were anal-
yzed to determine the information trans-
mission. It was found that head movement
gives a 40 percent improvement in depth

discrimination when the cube is between 50
and 100 cm from the subject than when the
cube is between 150 and 300 cm. Intensity
variation resulted in an much improvement
as head movement.

A number of experiments were done on the effectiveness

of "kinetic depth effect". This illusion was created by

modifying the Man Vehicle Laboratory 3-D display program

to show alternately views of a cube in two different posi-

tions. The "apparent motion" thus produced created the

movement necessary for observation of the kinetic depth

effect. Repetition rate, image brightness, apparent motion

and on and off times were varied. As expected, it was

found that at a repetition rate of approximately 3 cps,

most observers 'impleted' the two different views seen in

the presentation and 'saw' a moving cube as a three dim-

ensional object rather than a two dimensional figure whose

form was changing.

Creating continuous small apparent movements of the

cube did not, however resolve the basic perceptual ambiguity

associated with spatial relationships of the 'front' and

'back' lines of the cube, and subjects continued to report

Necker Cube reversals.

At the suggestion of Dr. Paul A. Kolers, the 3-D display

program was further modified to investigate the possibility

of creating a monocular, steroscopic image by using the

Schoen effect. It has been suggested that there is a def-

inite relationship between depth values, retinal input, image

arrival time at the visual cortex, and the creation of stereopsis. It was suggested that if left and right eye views of a carefully constructed scene are shown alternately, in proper stereoscopic cross registration on a screen, an observer should perceive a motionless object in three dimensional space. By carefully controlling the repetition rate (about 3 cps) and varying the off times, the display allegedly can be made to operate at one of the basic physiological refractory periods associated with the visual system.

Initial attempts to observe the effect with the 3-D CRT display were not encouraging. It was felt that the CRT phosphor persistence might be at fault, so lantern slide projectors were used to flash, alternately, left and right eye photographs of various simple geometrical objects (cone or cube) seen against a dark background. The repetition rate and the on and off times were controlled precisely. The observer's position was systematically varied so that objects projected on the screen subtended various angles on the retina. Ten subjects reported essentially the same results with one or both eyes: if the repetition rate were slow, the left and right eye views were seen alternately. Above 4 cps, all subjects saw the object in apparent oscillatory motion and the kinetic depth illusion was observed. In intermediate frequency ranges, with off times which seemed to vary from observer to observer, the object could no longer actually

be seen moving. Generally observers were aware that two views were being shown, but if asked where the object was located on the screen would report that its position was somewhat vague, but located somewhere between the screen positions of left and right eye views. Apparently, the observers received information from both the left and right eye views, for they generally perceived some three dimensionality in the geometric objects on the screen. However, no two people reported exactly the same perception. If the observer attempts to do more than just fixate blankly in the area of the object on the screen by looking at one particular part of the object, the illusion is destroyed and a new illusion of objectless pure motion replaces it. This concluded our research into this particular means of generating three dimensional displays.

2.2   GLIDE SLOPE – LANDING DISPLAY

The work on general 3-D displays led naturally to research on particular types of displays. One of these concerned a perspective display applicable to the aircraft landing situation. A new form of contact analog display using perspective vertical bars for glide slope indication was developed. This display and the method of evaluation are designed to emphasize the ease of learning to land a tilt-engine VTOL on different steepness glide slopes. This

work integrated several aspects of display information, pilot performance and handling of V/STOL aircraft from cruise to final touchdown, including transition, hover and landing.

The purpose of the study was to evaluate the display information presentation and human pilot performance. It concentrated on a novel contact analog display (perspective view of runway or landing site and glide path). The investigation considered:

1.   a.   Information available in a perspective display, giving the pilot a real outside world picture of runway and transition path.

      b.   Examination of components used for integration display, superimposed on the contact analog display, e.g. angle of attack, velocity vector.

      c.   Examination of the display elements, each giving some information, e.g. horizon for roll cue, intensity for depth cue.

      d.   Other display parameters, such as effect of screen size, display gain.

2.   a.   Pilot performance while landing, using a compensatory display overcoming common optical illusions.

      b.   The ability of a pilot to get familiar with a given display (learning curve for that display).

The basis for analysis of this portion is a measure of integrated weighted deviation from desired path. This figure was plotted versus history of the number of trials. The number of trials is determined by the asymptote of the learning curve, i.e. the steady state in the performance.

    3. a. The piloting technique for controlling the aircraft in the different phases of landing. A study of the pilot describing functions was made for the variables of interest including: forward speed, rate of climb, angle of attack, position, attitude, thrust, and engine tilt angle.

    4. a. Workload measurements were done by giving the pilot a secondary task.

Dr. Van Houtte's work on this project is summarized in the abstract of his doctoral thesis.

<div align="center">

DISPLAY INSTRUMENTATION FOR V/STOL AIRCRAFT
IN LANDING

N.A. Van Houtte

Sc.D. Thesis

Department of Aeronautics and Astronautics

1970

ABSTRACT

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This thesis concentrates on the instrumentation problem of aircraft facing the problem of steep angle approaches or landing in zero visibility.

A V/STOL aircraft (of the tilt engine type) has
been simulated using the non-linearized form of
the equations of motion, and has been flown from
cruise altitude to touchdown with severe wind
disturbances, descending along glideslopes of
4.47°, 8.87° and 17.3°.

Three kinds of instrumentation have been used:
a conventional set of cockpit-like instruments,
the same set augmented by means of a flight-
path profile display, and a contact analog
perspective glideslope indicating system.

A general display program has been written to
display a skeleton scenery, consisting of lines
connecting characteristic points. The lines
in this application are the runway boundaries,
the glideslope lines, and several distance
indicating poles. The display is generated on
a large screen cathode ray tube, using an analog
line drawing scheme. The picture changes dyna-
mically and is updated by a digital machine
sixteen times per second, using the translational
and rotational rates of change resulting from the
motion of the observer.

The piloting task consisted of staying level in
flight until the intercept of the glideslope,
then in tracking the glideslope to hover and in
landing the aircraft with minimum impact velocity
and maximum accuracy. The task was quite diffi-
cult, because of the lack of stability augment-
ation.

The value of the perspective glideslope indicating
system has been shown in:

1. The ease of performing coordinated
    maneuvers, allowing large but quite
    precise changes of flight variables.
2. the consistency of touchdowns
3. the accuracy of tracking the glide-
    slope, with dead beat response
4. the learning curve, and
5. the effectiveness of the presentation
    of the integrated real world outside
    picture.

2.3 VTOL INTEGRATED DISPLAY

Fundamental problems arose with VTOL integrated displays since the display is a combination of the vertical plane information (artificial horizon) with the horizontal situation indication. A new approach to this subject was a "bottom window" display in which pitch and roll are indicated by projections of aircraft planes on the ground plane. The CRT displays a grid painted on the ground, which moves aft along the display face to indicate forward velocity and sideways to indicate sideslip. Increasing altitude is indicated by decreasing grid size as compared to the reference square or "window" drawn on the lower half of the display face. When the grid size is identical to the window size, the aircraft is at zero altitude. The origin of the grid is at the center of the window. Locations of interest, e.g. landing sites, were marked on the grid with a prediction line showing computed future position. Heading is displayed alphanumerically at the top of the display with a prediction line showing computed future heading.

The attitude display was not the normal horizon line type display but rather shows the direction of the z axis of the aircraft. Thus roll will be indicated by displacement of a fore and aft line on the screen and pitch by displacement of a lateral line. When the aircraft is straight and level,

the intersection of the two lines will be in the center of the screen. Predicted pitch and roll will be indicated by a line emanating from the intersection of the pitch and roll lines. (Predictive display techniques were required for pilot stabilization of the unstabilized aircraft.)

The prediction times for the attitude indications were different from the prediction times for lateral indications, but both were computed using a much simplified set of equations which were used for the vehicle dynamics simulation.

The original development of the VTOL "bottom window" display for integrated horizontal and vertical situation information was completed by Major Gordon Kemp (CAF) as his Engineer's thesis in 1969. The abstract of his thesis, given below, describes the initial development work.

A VTOL PREDICTION DISPLAY

G.G. Kemp

Engineer's Thesis

Department of Aeronautics and Astronautics

1969

ABSTRACT

Prediction displays allow human operators to control difficult plants more precisely than conventional displays, and with decreased learning times. This thesis applies the principles of prediction displays to the VTOL control problem. A typical VTOL is simulated in six degrees of freedom on a digital computer. The computer is linked to a graphics terminal which is used to draw the proposed prediction display.

The display simulated is a "plan-view" display on which pitch and roll information is portrayed

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as projections of the aircraft Y-Z and X-Z
planes respectively, onto the ground. Pre-
diction information is displayed in attitude
and position.

Preliminary results show prediction to be
useful.   Further testing is required to
quantify these results.

A paper on this subject by L.R. Young is abstracted below.

INTEGRATED DISPLAY PRINCIPLES AND SOME
      APPLICATIONS TO V/STOL AIRCRAFT

L.R. Young

ABSTRACT

The arguments for integrating flight control
and guidance information in a single display
have been made repeatedly and have been proven
experimentally to be of value in V/STOL air-
craft. STOL steep glide-slope landings can
present challenging control problems. In ad-
dition to the use of stability augmentation
systems to ease the pilot's task, one is led
to techniques for displaying the relevant
flight control signals in a single area,
thereby reducing visual scanning and its
attendant time loss. One also tries to pre-
sent the information in a manner which helps
the pilot close each of the control loops in
a rapid, unambiguous, and nonfatiguing manner.
Although a number of VTOL integrated displays
have been successfully developed, the display
testing techniques are still largely empirical
and the displays seem to allow considerable
room for improvement. While nothing like a
useable theory for the design of integrated
displays yet exists, the lessons learned from
the experience of many integrated display dev-
elopments has led to some general principles
and guidelines. This paper discusses such
guidelines and illustrates some of their
applications.

2.4 ANTI-VERTIGO DISPLAY

Research on orientation and disorientation was performed not only to understand the basic mechanisms related to these topics, but was also aimed at arriving at ways to combat the deleterious effects of disorientation. The 3-D display described previously is one possible means. Others used models of the vestibular system to derive a "pseudostable" peripheral display which might reduce the onset of vertigo.

Man Vehicle Laboratory efforts to develop valid mathematical models for the semicircular canals and otoliths using the techniques of control theory were reviewed with a view toward defining and attempting to determine the etiology of vertigo and possible explanations for the apparently related motion sickness syndrome.

It became apparent that vertigo was a loosely defined term applied (often indiscriminately) to many types of perceptual illusions. Most studies have been aimed at determining the statistical relationship between perceptual disorientation and other forms of motion induced malaise and aircraft accidents.

We concluded that one basic circumstance associated with most cases of vertigo occurs when, because of the interaction of vehicle motions with human motion sensors and the nature of the visual field, a conflict arises when the human

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attempts subconsciously to continue the process, normally unimpeded, of establishing a conception of his dynamic oreintation in space.

It has been suggested by many that the occurrence of disorientation resulting from conflicting sensory modalities might be alleviated by a system which showed a vertiginous subject a display of the outside world oriented with respect to him so that it would agree with his subjective prediction of the orientation of the outside world based only on his nonvisual modalities. In essence, the conflict between visual and vestibular input, presumably the major source of conflict in most situations, would be resolved.

Our previous models of the human vestibular sensors and a control theory approach towards the problem of modelling the method which the human central nervous system uses to organize the motion sensing inputs suggested that initial steps should be taken to construct a prototype anti-vertigo display which would test the relevance of the conflicting sensory modality approach to the etiology of vertigo.

The basic concept of the anti-vertigo display is quite simple. Based on the motions of the vehicle, sensed in the frame of reference of the observer's head, the models of the various sensory modalities predict the inputs to the observers central nervous system. These are modelled in the display

system by a heuristic program which determines the observers concept of his spatial orientation based on non-visual modalities, and displays either peripherally or foveally his subjective orientation in a compelling fashion.

The prototype display was tested for one-axis stimulation. Experiments were undertaken in 1967 to investigate the visual and vestibular motion cue interaction. The laboratory's rotating chair was modified to produce a moving stripe display on a screen inside the cab. Subjects were seated in the closed cab and stimulated so as to experience a simple form of vertigo, "dizziness", which results from a lingering sensation of rotation after a cessation of angular velocity. A non-rational-parameter computer model for human vestibular response to angular acceleration in a horizontal plane was used to control the moving bar display, thus creating a visual input which could be made to agree or disagree with the theoretical subjective sensation of motion relative to the outside world.

Preliminary experiments involved four types of tests on five subjects. Subjects were asked to indicate the onset of sensation of rotation by pushing a bi-directional switch, and to signal each ninety degrees of additional rotation in that direction. In addition, subjects were told to indicate when they felt confused in that they could no longer determine their subjective angular velocity. No confusion was

reported when the display was driven so that the visual cue was sympathetic to the theoretical subjective angular velocity profile, even though it was not identical with the actual chair velocity. However, every subject reported confusion either when the display was anti-sympathetically driven or when the visual input was driven so that it was stabilized with respect to the outside world.

One interesting aspect of this series of experiments is the observation that in the negative (anti-sympathetic) driven experiments, the subjective velocities reported during the first twenty seconds were higher than those experienced in the case where the display is positively driven. A possible explanation for this may be that while the visual vestibular conflict is not sufficiently great to create vertigo, an interaction between optokinetic and vestibular nystagmus may be taking place which results in the bar velocity being perceived as substantially greater than it actually is. Indeed, the whole question of nystagmic interaction needed investigation. Tests showed that a moving display could readily elicit optokinetic nystagmus, while other tests with the display stationary in a rotating cab showed that surpressed vestibular nystagmus was also present. Most subjects in the major experiments reported that they occasionally could feel nystagmic movements as they attempted to fixate on the cross in the display center.

In general, however, it could not be concluded from that

test that the visual input exerted any sort of linear pro-
portional moderating influence on the magnitude of the sub-
jective velocity reported. One can conclude that subjects
generally reported a subjective velocity which was vestibular
in origin. When presented with a conflicting visual cue,
they simply chose to ignore it as best they could.

The form of the subjective response did tend to
support the predicted response from the adaptation model for
rotation sensation, although intersubject variances were
sufficiently large as to make average data meaningless. Also
there was no obvious habituation to the repeated vestibular
stimulus pattern in the responses as reported. Peak velocities
are not necessarily lower for later runs in the test series.

The following results can be presented:

1. The display system is moderately visually compelling
   in this experiment. In the presence of a conflicting
   visual cue, subjects either became confused or
   report subjective velocities which are evidently
   primarily vestibular in origin.

2. No vertigo was reported when the display was driven
   so that the visual cue was sympathetic to the adapt-
   ation model for vestibular sensation. On the other
   hand, every subject reported confusion when the bars
   were either negatively driven or stabilized in space.

3. In the presence of conflicting cues, subjects are sometimes able to eliminate confusion by surpressing the visual cue.

4. However, motion sickness evidently cannot easily be avoided in the presence of conflicting cues. No experiments were exhaustively run to determine if a positively driven display could alleviate motion sickness to any statistically verifiable degree.

5. Influences of habituation were not demonstrably present; however, the occurrences of velocity overshoot suggest that adaptation is taking place and tend to support the adaptation model.

6. Nystagmus is definitely present during display operation. The interaction between, and effects of, optokinetic and vestibular nystagmus on the subjective response could not be determined.

This work was reported in the Master's Thesis of Charles M. Oman.

INFLUENCE OF ADAPTATION ON THE HUMAN SEMI-
CIRCULAR CANALS AND THE ROLE OF SUBJECTIVE
ANGULAR VELOCITY CUES IN SPATIAL ORIENTATION

C.M. Oman

Master's Thesis

Department of Aeronautics & Astronautics

1968

ABSTRACT

The role of the semicircular canals in
human dynamic spatial orientation was
studied. A working definition for vertigo

was developed based on the assumption that
conflicting sensory modalities are the pri-
mary etiological factor.

Experiments were undertaken to investigate
the interaction between visual and vestibular
motion cue inputs. A non-rational parameter
model for human vestibular response to angular
acceleration in a horizontal plane was used
to control a moving bar display which showed
subjects seated inside a rotating chair cab
a visual input which could be made to disagree
or agree with the theoretical subjective sen-
sation of motion relative to the outside world.

The study led to an improvement in the math-
ematical model for subjective response and
compensatory eye velocity by including the
effects of short term adaptation. By assuming
that the physical canal dynamics were second
order and that the adaptation mechanism in-
volves a short term homeostatic shift in the
zero response reference level, some of the
persistent difficulties with the classical
"torsion pendulum" model were overcome.
Difference in nystagmus and subjective cupulo-
grams, as well as phase and time course data
were explained. Experimentally observed
"subjective undershoot" and "secondary nys-
tagmus" were accounted for.

The results of display experiments involving
four types of tests on five subjects indicated
that in the presence of a conflicting visual
cue, subjects either became unable to assess
their angular velocity, or reported subjective
velocities which were primarily vestibular in
origin. No confusion was reported when the
display was driven so that the visual cue was
sympathetic to the theoretical subjective
response. However, every subject reported
confusion when the display was anti-sympathet-
ically driven or when the visual input was
driven so that it was stabilized with respect
to the outside world.

This line of research, on visually induced motion cues and visual-vestibular interaction, has since led to a major activity in our laboratory. Applications to flight simulation technology are being supported by NASA Langley Research Center and applications to weightlessness by NASA Ames Research Center.

The early work on displays is summarized in the following paper:

THREE DISPLAY TECHNIQUES AT THE MAN VEHICLE LABORATORY

L.R. Young, C.M. Oman, R.M. Vircks, N.A. Van Houtte, and G.G. Kemp

ABSTRACT

Three display techniques designed to reduce man's uncertainty about his spatial orientation are presented:

1) A 3-D display system is described in which a simple computer generated CRT contact analog system is controlled by movement of the observer's head, as well as by vehicle motion.

2) A prototype VTOL guidance and control display is being developed. All attitude and guidance cues are presented on an integrated horizontal situation display in which pitch and roll angles appear as vehicle axis projections, and predictive display of attitude and position is used.

3) An "anti-vertigo" research display is being developed in which visual-vestibular conflict is reduced by driving a rotating visual field at rates determined by a mathematical model for vestibular function.

2.5 AUDITORY DISPLAYS

A different sort of display was investigated by P. Mirchandani as part of his Master's Thesis work. This was an auditory display which used variations in frequency and volume as error signals.

EVALUATION OF A SUPPLEMENTARY AUDITORY DISPLAY
IN A DUAL AXIS COMPENSATORY TRACKING TASK

P.B. Mirchandani

Master's Thesis

Department of Aeronautics and Astronautics

1971

ABSTRACT

This study was concerned with the evaluation of an auditory display technique in a dual axis tracking task. The auditory display was used as a supplement to a visual display.

Subjects were presented with two control tasks. The primary task was the control of an inertia plant (with dynamics represented by $1/s^2$). The secondary task was velocity control (dynamics represented by $1/s$). The errors for both the tasks were shown on separate visual displays. The object of the experiment was to investigate the effects on performance when the secondary task was supplemented with an auditory display. The auditory display consisted of a frequency-volume regulator: a positive error increased the volume and the pitch, and a negative error increased the volume but decreased the pitch. Two performance measures were obtained, the integral square error (ISE) and the describing function of the human operators.

Statistical analysis on the ISE performance measures indicated that when the secondary

task was supplemented with the auditory display, there was an improvement in performance of the secondary task at a 0.001 level of significance. The improvement in performance of the primary task was at a significance level of 0.1. The variance of the ISE performance measures, for both the tasks, decreased; this indicated a more consistent behavior with the auditory display.

The describintg function analysis showed that supplementing the secondary task with an auditory display increased the gain of the human operator for this task. The describing functions for the primary task did not show any apparent changes.

This work was also published in the IEEE Transactions on Systems, Man and Cybernetics.

AN AUDITORY DISPLAY IN A DUAL AXIS TRACKING
TASK

P.B. Mirchandani

ABSTRACT

An auditory display in a dual-axis compensatory tracking task was studied. Subjects were presented concurrently with the primary task of controlling a second order plant and the secondary task of controlling a first order plant. The plant errors for the two plants were shown on separate visual displays. An auditory display whose output varied in frequency and volume with the error was used to supplement the secondary taks on half of the runs. To study the effects of the auditory display, two performance measures were obtained: (1) the integral of the squared error (ISE) and (2) the describing functions of the human operators.

Statistical analysis of the ISE measures
indicated that when the secondary task
was supplemented with an auditory display,
there was a significant improvement in
performance on the secondary task. The
performance on the primary task improved
on the average, but not significantly.
The variances of the ISE values decreased
for both the tasks, indicating a more
consistent behavior with the auditory
display. The describing function analysis
showed that supplementing the secondary
task with the auditory display increased
the low frequency gain of the human oper-
ator for this task. The describing func-
tion for the primary task did not show
any apparent changes.

III

SENSORY PERCEPTION

3.1 VESTIBULAR SYSTEM

A prime goal in the research carried out under the
subject grant was obtaining a better understanding of the
effect of motion on the ability of men to perform a variety
of control actions. The otoliths and semicircular canals
making up the vestibular system in man required fuller
exploration. Consequently an extensive experimental and
analytical study of the dynamic characteristics of these
sensors was undertaken, using our two axis angular motion
simulator and one axis linear motion simulator. Many of
the results of our early work were presented in the doctoral
thesis of Dr. Jacob Meiry, abstracted below.

THE VESTIBULAR SYSTEM AND HUMAN DYNAMIC
SPACE ORIENTATION

J.L. Meiry

Sc.D. Thesis

Department of Aeronautics and Astronautics

1965

ABSTRACT

The motion sensors of the vestibular system
are studied to determine their role in human
dynamic space orientation and manual vehicle
control. The investigation yielded control
models for the sensors, descriptions of the
subsystems for eye stabilization and demon-
strations of the effects of motion cues on
closed loop manual control.

Experiments on the abilities of subjects to
perceive a variety of linear motions provided
data on the dynamic characteristics of the
otoliths, the linear motion sensors. Angular
acceleration threshold measurements supplemented
knowledge of the semicircular canals, the angular
motion sensors. Mathematical models are pre-
sented to describe the known control character-
istics of the vestibular sensors, relating
subjective perception of motion to objective
motion of a vehicle.

The vestibular system, the neck rotation pro-
prioceptors and the visual system form part
of the control system which maintains the eyes
stationary relative to a target or reference.
The contribution of each of these systems was
identified through experiments involving head
and body rotations about a vertical axis. Comp-
ensatory eye movements in response to neck
rotation were demonstrated and their dynamic
characteristics described by a lag-lead model.
The eye motions attributable to neck rotations
and vestibular stimulation obey superposicion
when both systems are active.

Human operator compensatory tracking is invest-
igated in simple vehicle orientation systems
with stable and unstable controlled elements.
Control of vehicle orientation to a reference
is simulated in three modes: visual, motion
and combined. Motion cues sensed by the vest-
ibular system and through tactile sensation
enable the operator to generate more lead
compensation than in fixed base simulation
with only visual input. The tracking per-
formance of the human in an unstable control
system near the limits of controllability
is shown to depend heavily upon the rate infor-
mation provided by the vestibular sensors.

The control models for the vestibular system which had

previously been developed elsewhere for the semicircular canals

and in this laboratory for the otoliths, were based on output

measurements (subjective sensation or objective recording s

such as of eye movement). In order to ascertain that these

transfer functions indeed did apply to the vestibular system, as opposed to tactile or visual inputs, one could either eliminate the other sources of input wholly or partially, or take the alternate approach of using subjects with known defects or complete absence of a functioning vestibular system. The latter approach was used in our experiments with the Navy, in which eleven carefully selected subjects with well-known defects of the gravity receptors or semicircular canals participated in a week's testing. The experiments paralleled earlier tests done in creating models for normals and included eye movement measurements and threshold determination for linear and angular accelerations, subjective perception of phase for linear oscillations, and the ability to control a simulated unstable vehicle with and without motion cues.

An early summary of this research was presented to the National Academy of Sciences Workshop on Orientation in the Exploration of Space in a paper abstracted below.

CONTROL ENGINEERING APPROACHES TO HUMAN DYNAMIC SPACE ORIENTATION

L.R. Young, J.L. Meiry, Y.T. Li

ABSTRACT

This paper reviews briefly some of the research that has been underway at MIT in the last few years, at the Man Vehicle Control Laboratory, in the Department of Aeronautics and Astronautics. It covers work on mathematical descriptions of the input-output relations characterizing vestibular mechanisms and some work on eye stabilization, including the influence of vestibular inputs, neck proprioceptive inputs, and fixed head visual tracking. Finally results are presented relating the vestibular research to descriptions of man as a member of a closed loop control system controlling the orientation and position of a vehicle. We have concentrated on visual input, tactile input and vestibular input, when these are either in agreement or in conflict.

At the output end, we considered not only the usual joystick hand control, but also postural control as a possible output mechanism. Another study deals with the adaptive mechanism for manual control. Naturally, the purpose of this study is to achieve a sufficient mathematical description of the human as an input-output device or set of devices, including all the nonlinearities and the statistical nature of the random components, to permit

the control systems engineer to make
rational quantitative estimates about
what the reactions of a man will be
in a piloting type task.

At this time work was also begun on the biophysics
of the vestibular mechanism including physical analyses
of the thermodynamics involved in the caloric response of
the semicircular canals, the fluid dynamics of the canals
when subjected to rotation, the interaction of linear and
angular motions on the semicircular canals, and the mech-
anisms of simultaneous rotation about two axes as sensed
by the vestibular system. One of the difficulties in
performing such analyses was the lack of data on certain
physical parameters associated with the vestibular system.
Consequently instrumentation was developed for measurement
of viscosity in small samples of endolymph at various temp-
eratures. Samples of cat and human endolymph were studied.

Viscosity measurements showed that the viscosities
of human endolymph did not vary appreciably with viscometer
inclination, although the terminal velocity of the rolling
spheres did change. Measurements after setting, showed that
there was no appreciable change. Thus it appears that endo-
lymph is not a shear thinning fluid, nor does its viscosity
change with "setting time"; further its chemical analysis
shows a low protein content typical of Newtonian Biological
fluids.

Work in the area of fluid dynamic analysis of the semicircular canal as a "rigid canal" has led to a system describing function of the form:

$$\theta_c(s)/\alpha = \sum_{i=1}^{\infty} A_i/s^2 + 2\zeta_i\omega_i s + \omega_i^2$$

where θ_c = cupula displacement

α = angular acceleration

and A_i, ζ_i and ω_i are functions of the viscosity of the fluid, coeffeicients of zero order Bessel functions and the "spring constant" of the cupula.

These measurements and other related work are summarized in the thesis of R. Steer, which was performed under NASA Grant NGR 22-009-156, but which has been of much use to our work under the subject grant.

THE INFLUENCE OF ANGULAR AND LINEAR ACCEL-
ERATION AND THERMAL STIMULATION ON THE
HUMAN SEMICIRCULAR CANALS

R.W. Steer

Sc.D. Thesis

Department of Aeronautics and Astronautics

1967

ABSTRACT

The hydrodynamic properties of the human semicircular canal system were studied to determine its dynamic characteristics and their relationship to observed subjective and objective vestibular responses to various motion inputs. Four topics of particular importance in current vestibular research were examined in detail.

The density, coefficient of expansion, and viscosity of the labyrinthine fluids, endolymph and perilymph, have been measured to provide precise values for the coefficients of the dynamic models. A microviscometer was designed, built, calibrated, and used to measure the viscosity of 1-2 microliter samples of endolymph and perilymph. Density measurements were made via precision balance scales and accurate volume measurements and coefficients of expansion measurements were made by microscopic measurements of the volume of the fluids at several temperatures.

The semicircular canal is modelled as a rigid torus of fluid, with the cupula acting as an elastic and viscous restraint. A system transfer function is evaluated for the cupula displacement as a function of angular acceleration. It is shown that the cupula's effective inertia and viscous drag on the wall of the membranous labyrinth influence the dynamic performance of the system but do not resolve the disparity between previous calculations of damping, which only considered hydrodynamic drag of endolymph in the canalicular duct, and experimentally measured damping coefficients.

Caloric stimulation of the vestibular apparatus is examined, and a model is proposed, based on the published measured time history of the temperature gradient across the lateral canal when the external auditory meatus is irrigated with water above or below body temperature. The presence of a thermal gradient across the lateral canal is shown to produce the physiological equivalent of an angular acceleration because of the torque which acts on the endolymph as a result of its thermal coefficient of expansion. Caloric experiments were performed which attest to the validity of the model.

The influence of linear acceleration on the semicircular canal was investigated. Human objective and subjective responses to rotation about a horizontal axis, to counter-rotation and to stimulation by a rotating acceleration

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vector were examined. The observed responses
of long duration nystagmus and continuous sens-
ation of rotation are not in conformity with
classical models of the vestibular system and
there has developed a sizable body of experi-
mental evidence which attributes a significant
portion of these unusual responses to the
semicircular canals. It is shown through
the distensibility of the canalicular duct
udner the influence of linear acceleration,
that the observed bias component of nystagmus
can be attributed to a first order nonlinearity
of the semicircular canal dynamics. Experiments
were performed on a centrifuge equipped with a
rotating chair to show the relationship between
the magnitude of the acceleration field, the
rotation rate of the subject and the slow
phase velocity of vestibular nystagmus.

Two additional papers by Dr. Meiry were presented

summarizing much of this work. These papers are abstracted

here.

A MATHEMATICAL MODEL FOR THE NECK RECEPTORS - OCULAR REFLEX

J.L. Meiry

ABSTRACT

Lateral eye movements are controlled by multi-
input servo control system with inputs to it
by the vestibular system and the neck receptors,
by the eye itself and by the voluntary tracking
intentions of humans. This control system
rotates the eye in order to maintain the image
of an object of fixation upon the retina. A
displacement of this image is caused by the
motion of the visual target and by rotations
of the head on the body. The eye movement
control system responds to these disturbing
motions with two different modes of eye move-
ments: tracking and compensatory movements.
Tracking eye movements follow the moving

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target in the visual field. Compensatory eye movements rotate the eye in a direction opposite to the rotation of the human body. Although the role of neck receptors as a source of compensatory eye movements has been suggested by physiologists, their participation in the control system has not been assessed previously. In the experimental series reported here, these eye movements are shown to obey a simple lag-lead model.

A MODEL FOR OTOLITH AND ITS IMPLICATION ON HUMAN SPATIAL ORIENTATION

J.L. Meiry

ABSTRACT

The dynamic characteristics of the otoliths are investigated by measurements of human subjective perception of motion. A series of psychophysical experiments relates the human's sensation of motion to the imposed motion pattern. Since a pure linear motion simulator was used throughout the reported experiments, the otoliths are presumably the only part of the vestibular system which is stimulated, and the measured response is free of sensor interaction effects.

Dynamically, the otoliths are linear velocity meters for motions with frequencies within the range 0.016 cps to 0.25 cps. The threshold of perception of linear accelerations is about 0.005 g in the plane of the otoliths. A mathematical model for the otoliths represents the dynamics of the sensors to consist of a linear second order portion followed by a non-linearity corresponding to the threshold of perception.

Based on further consideration of the nature of the otolith response mechanism, a revised dynamic model of the otolith was formulated. The model gave good agreement with known test data on perception of tilt or linear acceleration and eye counterrolling data. The model is described in a paper presented at the Third Symposium on the Role of the Vestibular Organs in Space Exploration.

A REVISED DYNAMIC OTOLITH MODEL

L.R. Young and J.L. Meiry

ABSTRACT

The basic dynamic model of Meiry was based on observed relations between the perceived direction of linear motion and input acceleration. Although this model correctly predicted phase of perceived velocity for lateral oscillation and time to detect motion under constant acceleration, it failed to account for at least two important observations:

1. Behavioral and electrophysiological data indicate a sustained steady otolith output to sustained tilt angle. The models perceived acceleration or tilt output decayed to zero with a time constant of 10 seconds.

2. Dynamic counterrolling data agree with the model at higher frequencies. The experimental counterrolling at

zero frequency, however, indicates
a static component of otolith out-
put with no phase lag referred to
acceleration, whereas the model had
no static output and approached 90
degrees of lead at zero frequency.

At the suggestion of Dr. H. Von Gierke, a
static component was included in the otolith
model.   This revised linear model allows
steady state response to acceleration.

The revised linear model will act approxi-
mately as a velocity transducer over the
mid-frequency range. The transfer function
from specific force or lateral acceleration
has a static sensitivity of 0.4.

Another paper on the subject of vestibular models

was presented by Professor L.R. Young.

ON THE BIOCYBERNETICS OF THE VESTIBULAR SYSTEM

L.R. Young

ABSTRACT

The human vestibular system for dynamic
space orientation is described mathemat-
ically, using the identification methods
of control theory. A biocybernetic model

is useful in predicting man's perceived
orientation in space, postural reactions,
nystagmus eye movements, and piloting
actions based on motion cues. The semi-
circular canals, which act as angular
velocity sensors, have been subjected to
a fluid dynamic analysis. The limitations
of the torsion pendulum model are examined
and a quantitative description of adapta-
tion is proposed. An otolith model,
responding to linear acceleration forces,
is presented and shown to agree with the
perception of tilt and translation, eye
counterrolling, and electrophysiological
data. Cross coupling effects are discussed,
including the influence of linear acceler-
ation on the semicircular canals.

A summary of modelling efforts was pre·ented by

L.R. Young in the paper abstracted below.
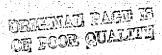
THE CURRENT STATUS OF VESTIBULAR SYSTEM MODELS

L.R. Young

ABSTRACT

The human vestibular system for dynamic
space orientation is described mathemat-
ically, using the identification methods
of control theory. The analysis by
several investigators at the Man Vehicle
Laboratory, M.I.T., building on the
available data, has led to a biocyber-
netic model which is useful in predicting
man's perceived orientation in space,
postural reactions, nystagmus eye move-
ments, and piloting actions based on
motion cues. The semicircular canals,

which act as angular velocity sensors, have
been subjected to a fluid dynamics analysis.
The limitations of the torsion pendulum
model of Van Egmond, Groen and Jongkees are
examined, and a quantitative description of
adaptation is proposed. An otolith model,
responding to linear acceleration forces,
is presented and shown to agree with the
perception of tilt and translation, eye
counterrolling, and electrophysiological
data. Cross-coupling effects are discussed,
including the influence of linear acceler-
ation on the semicircular canals.

One of the techniques available for exploring

habituation and adaptation effects involves the separation

of two paths in higher mental processing of vestibular data:

the subjective sensation of rotation reported by the subject,

and the nystagmoid eye movements objectively recorded. Pre-

liminary data suggested that a possible hysteresis component

in semicircular canal function might be responsible for the

difference between subjective and objective phase lag for

sinusoidal rotations. Work on this aspect of the problem

led to a Master's Thesis by G.B. Katz.

PERCEPTION OF ROTATION: NYSTAGMUS AND SUB-
JECTIVE RESPONSE AT LOW FREQUENCY STIMULATION

G.B. Katz

Master's Thesis

Department of Aeronautics and Astronautics

1967

ABSTRACT

A rotating chair was built to submit subjects
to sinusoidal angular acceleration levels at
various combinations of frequencies (0.01 cps
to 0.1 cps) and peak angular acceleration
levels (10 deg/sec^2 to 45 deg/sec^2) for the

purpose of studying the human subjective and objective response to rotation at low frequencies. Each of four subjects was seated in the completely dark chair with the axis of rotation passing through his head.

His subjective response was measured by means of a directional switch; his objective eye movement response was simultaneously measured and recorded. A study of the resultant phase differences between both subjective and objective perceptions or angular velocity and actual angular velocity leads to the following conclusions:

1. The phase lead of both objective and subjective response exhibited no simple functional dependence on amplitude of acceleration.

2. The amount of phase lead in both cases is inversely proportional to stimulus frequency

3. The objective phase lead is larger at any stimulus condition than the corresponding subjective lead.

4. Intersubject response differences were very evident, irregular and relatively great.

5. The data presented agrees in a gross manner with the data of Hixon and Niven.

We have attempted to extend the body of data on low frequency sinusoidal stimulation of the linear acceleration sensors to below our previous limits of 0.1 rad/sec., which represents the limitation on the thirty-two foot length of our acceleration track. In a series of experiments, subjects were oscillated at very low frequencies about the roll axis

in our NE-2 simulator in an attempt to introduce sinusoidal stimulation to the y-axis of the otoliths while maintaining the angular acceleration and angular velocities below canal threshold. Although the subjective phase lag data (phase of subject's identification of velocity reversal with respect to actual velocity reversal) did indeed show the low frequency phase peak predicted by the model, the data did not overlap or tie in with the previous experimental data taken on the linear acceleration cart. A number of possible explanations for this phenomenon have been considered including the non-uniformity of the NE-2 rotation and the inherent canal stimulation associated with a rotating specific force vector.

Professor Young presented two papers in 1968 dealing with the vestibular system and its relationship to control.

FUNCTIONS OF THE VESTIBULAR SYSTEM IN GUIDANCE AND CONTROL

L.R. Young

ABSTRACT

A physical analog model of the vestibular system was developed for research purposes. The model consists of a three gimbal "head" containing three rate gyroscopes and six linear accelerometers, and a special purpose analog computer simulating the dynamics and the non-linearities of the non-auditory labyrinth.

The vestibular package can be rotated through
normal head movements by the machine and
mounted on a centrifuge or flown to measure
actual motion inputs. The distance between
the "ears" is adjustable, as well as the
orientation of the sensitive direction of
each canal and otolith axis. The computer
console permits adjustment of the important
gains, nonlinearities and time constants of
the vestibular system for utility in refin-
ing models, training physiologists, predict-
ing orientation perception or nystagmus and
for aids in design of moving base simulators
or artificial g platforms.

MOTION CUES AND VESTIBULAR MODELS

L.R. Young

ABSTRACT

The evolutionary process has given us a
highly developed visual system, on which
all sighted people rely for their primary
sense of orientation and motion, as well
as for information transfer. The impor-
tance of quantitative models for visual
function is reflected in the enormous
engineering psychology literature cover-
ing such visual "design problems" as
color sensitivity, adaptation, acuity,
contrast, time-intensity tradeoffs,
motion perception, and a variety of opti-
cal illusions.

By way of contrast, the function of the
vestibular system is virtually unknown to
the average engineer. The vestibular
system, comprising the membranous non-
auditory labyrinths in the inner ear,
serves as a fast, rough, inertial system
to enable man to adjust his posture to
avoid falling down, to sense his position
and velocity, and to direct and stabilize
his eyes in order to take in visual infor-
mation while moving. Most of us are only
aware of this motion sensing system when
it causes difficulty. In addition to

motion sickness (which may be attributed to visual-vestibular conflict), we are concerned with vestibular contributions to disorientation and vertigo, and nystagmus (rhythmic motion of the eyes which may interfere with reading displays). We must also consider the long term adaptation effects possible with the unusual motion environment under weightlessness, reduced gravity, or in a rotating spacecraft. On the positive side, it is important to note that the presence of vehicle motion (as opposed to "fixed base" simulation) generally makes any vehicle easier to fly and aids pilot performance. To be specific, the motion cues seem to aid pilot performance most for vehicle motions in the frequency range of high sensitivity of the vestibular system.

For all of these reasons, as well as for its possible clinical value, we are developing a quantitative mathematical model for the vestibular system, relating the time history of linear and angular motions to non-visual perception of orientation, motion, and nystagmus. The models we are developing are "input-output" models; however, in each case we attempt to relate the parameters of the model to known physiological characteristics. The engineering interest in the vestibular system as a component of man's "attitude control system" has led us also to build a physical analog of the vestibular system, using gyros, accelerometers, gimbals, and a special purpose analog computer.

The directional preponderance associated with the semicircular canal indicates the direction and magnitude of the spin that the subject "feels" in the absence of any average angular velocity. The nature of this directional preponderance is of considerable interest clinically and in screening and matching certain dynamic displays to individual pilots. We explored a "natural stimulation" psychophysical

as an alternative to the caloric testing usually used for directional preponderance studies. Seven subjects were tested in our servo-driven single axis yaw chair (subject to zero mean random disturbances). Subjects all had eyes open in the dark. They tried to control the chair to keep it stationary while we recorded the resulting drift of the chair in one direction or the other. In the experiments conducted, all subjects showed a tendency to rotate in a preferred direction without being aware of this fact. Of the seven subjects tested, three always drifted in one perferred direction and the rest drifted in a preferred direction at least eighty percent of the time. It was further noticed that each subject tended to drift in his preferred direction at a constant angular acceleration. The mean average of angular acceleration of the subjects in their preferred direction of rotation was 0.16 rad/sec^2. The subjects were given a thorough vestibular examination by Dr. A. Weiss of the Massachusetts Eye and Ear Infirmary. The "reduced vestibular response" (sensitivity of one ear as compared to the other on the basis of caloric responses) were obtained with eyes open and closed. The clinical directional preponderance (perponderance in one direction of nystagmus as compared to the other direction) in duration and slow phase velocity of the subjects were also calculated, both with eyes open and closed.

Although high correlation was not observed between these tests and those run on the rotating chair, there seems to be significant binary correlation between the reduced vestibular response, with eyes opened, and the directional preponderance as measured with the rotating chair. Five of the six subjects tested showed reduced vestibular response in the ear corresponding to the preferred direction of rotation. This would mean that the subjects whose left ear was more sensitive to caloric testing usually tend to drift to the left.

Having made significant progress in modelling at least one of the adaptation phases of vestibular response, we began to consider the more challenging problem of habituation to specific or general classes of motion stimuli. The kinds of habituation which could be included are the pilot's ability to subjectively ignore and in fact to inhibit nystagmus as a result of motion, the "sea legs" phenomenon, the skater's or actobat's habituation to bizarre stimulation such as is experienced in prolonged turning (this might be observed in moving about in a rotating spacecraft). There was relatively little data available in these areas and the performance of experiments on these types of habituation is difficult. However, using behavioral tests on humans, especially the results of Dr. Graybiel's slow rotating room experiments at Pensacola, and a number of fine habituation experiments in cats, we tried to develop a theory for habituation of vestibular responses which would at least allow predicting of

disorienting situations. Our basic notion consisted of a
model for habituation which involved an internalized model
of the environment against which all vestibular responses
are compared, with only deviations from the expected stimuli
transmitted.

As a beginning we studied the response of subjects to
prolonged rotational stimuli in the horizontal plane. Results
of this study led to the adoption of separate time constants
for adaptation for nystagmus and subjective sensation.

A paper by Young and Oman gives an overview of this
stage of the model.

MODELLING ADAPTATION IN THE HUMAN SEMICIRCULAR RESPONSE TO ROTATION

L.R. Young and C.M. Oman

ABSTRACT

The mathematical description for human semi-
circular response can be improved by the
addition of adaptation dynamics in the path-
ways to subjective and nystagmus response.
Adaptation is represented as a shifting ref-
erence level based on the recent history of
cupula displacement.

A similar paper on the horizontal adaptation appeared
in Aerospace Medicine.

A MODEL FOR VESTIBULAR ADAPTATION TO HORIZONTAL ROTATION

L.R. Young and C.M. Oman

ABSTRACT

Short term adaptation effects are seen in
subjective sensation of rotation and vest-
ibular nystagmus. The mathematical model
for semicircular canal function is improved
by the addition of two adaptation terms
(approximately one-half minute time constant
for sensation and two minute time constant
for nystagmus) to the overdamped second
order description. Adaptation is represented
as a shift of reference level based on the
recent history of cupula displacement. This
model accounts for the difference in time
constants between nystagmus and subjective
cupulograms, secondary nystagmus and the
decreased sensitivity to prolonged acceler-
ation.

Professor Young presented a paper to the AIAA in 1971
which discussed these problems as they might be encountered
in a rotating spacecraft.

MODELLING HUMAN DISORIENTATION IN A ROTATING
SPACECRAFT

L.R. Young

Presented to the AIAA/ASME Weightlessness
and Artificial Gravity Meeting, Virginia
1971: AIAA Paper No 71-870.

ABSTRACT

The problem of disorientation in a rotating
spacecraft is treated as an example of the
general case of habituation to an unusual
motion environment using all sensors and
active movements. The dynamic response of
the sensors is stressed. Several avenues
for work on combatting disorientation are
mentioned.

A textbook presentation by Professor Young appeared
in Vernon Mountcastle's Medical Physiology, in 1974. This
chapter treats the many aspects of the vestibular system in
detail and its introduction is reproduced below:

ROLE OF THE VESTIBULAR SYSTEM IN POSTURE AND MOVEMENT

L.R. Young

Chapter 27, Medical Physiology, Volume I,
Vernon Mountcastle, Editor.   C.V. Mosby
Co, St. Louis, MO. 1974.

INTRODUCTION

The nonauditory portion of the inner ear
consists of a highly specialized set of
fluid-filled tubes (semicircular canals)
and otoliths, collectively known as the
labyrinth or vestibular system.   The vest-
ibular apparatus in man serves three major
functions: (1) as the primary organ of
equilibrium, it plays a dominant role in
the subjective sensation of motion and
spatial orientation; (2) vestibular inputs
to the postural control system elicit
adjusment of muscle activity and body posi-
tion to prevent falling; (3) vestibular
influences on eye movements tend to stabi-
lize the eyes in space during head movements,
thereby reducing the movement of the image
on the retina.

The "inputs" to the system are linear and
angular motions of the head.   In the classic
view of the system the three semicircular
canals in each ear respond primarily to
angular acceleration of the head, and the
sensory afferents indicate angular velocity
of the head over the usual physiologic range
of movements.   The otoliths, responding to
gravity and linear acceleration, are also
known as statoliths or graviceptors, terms
that emphasize their role in signaling the
static orientation of the head with respect
to the real or apparent vertical.   Labyrin-
thine signals are combined with visual,
exteroceptive, interoceptive, and occasion-
ally, auditory sensory signals in the com-
plex closed loop processes of spatial
orientation and maintenance of equilibrium.

The effect of the acceleration stimuli on
the individual canals and otoliths depends
on their orientation, which in turn is
determined by the orientation of the head
in space. Nystagmoid eye movements are
generated on the basis of vestibular out-
puts, but these eye movements do not in
turn affect the vestibular system directly.
However, the vestibular regulation of
equilibrium through head and body movements
is a closed-loop feedback system, since
the labyrinth moves with the head. The
resulting head and body motions can be used
to null the "closed-loop error", which
signals departure from equilibrium or from
a planned trajectory.

One of the persistant conceptual difficulties with
the laboratory's model for human response to rotation was
the representation of the threshold to acceleration. A
direct simple threshold in the form of a deadzone to angular
acceleration had been ruled out because of the relationship
between stimulus angular acceleration and the onset of
sensation. In his 1965 model, Meiry included a threshold
based on the deviation of the cupula, although he noted
that this representation should not be taken literally.

In the later model of Young and Oman, we reinterpreted
the threshold to be a deadzone operator acting on the cupula
signal after an adaptation opertor, with the input having
the dimensions of angular velocity. While this configuration
facilitated correlation with available data, a number of

objections have been raised about it. This line of

research was continued under another NASA Grant, NGR

22-009-701, entitled "Research on the Integration of

Visual and Motion Requirements for Flight Simulation

and Ride Quality Investigation" (NASA Langley Research

Center). A much improved model for the vestibular

system resulted and is summarized here in the thesis

of Charles C. Ormsby. The abstract is given below.

MODEL OF HUMAN DYNAMIC ORIENTATION

C.C. Ormsby

Ph.D. Thesis

Department of Aeronautics and Astronautics

1974

(This thesis was also reproduced as a NASA
Contractor Report, CR-132537
1974)

ABSTRACT

The dynamics associated with the perception of
orientation were modelled for near-threshold
and suprathreshold vestibular stimuli. A model
of the information available at the peripheral
sensors which was consistent with available
neurophysiological data was developed and served
as the basis for the models of the perceptual
responses. As a preliminary assumption, the
central processor was presumed to utilize the
information from the peripheral sensors in an
optimal (minimum mean square error) manner to
produce the perceptual estimate of dynamic
orientation. This assumption, coupled with

the models of sensory information determined
the form of the model for the central pro-
cessor. Comparison of model responses with
data from psychophysical experiments indicated
that while little or no central processing may
be occuring for simple suprathreshold canal
stimulation, a significant portion of the
dynamic response to translational accelerations
must be attributed to the central processing
of otolith information.

The fundamental mechanism which underlies the
phenomenon of vestibular thresholds was studied
experimentally by testing the response of sub-
jects to a near threshold stimulus consisting
of a velocity step-ramp proporational to the
sum of the subject's velocity step and accel-
eration step thresholds. Experimental results
indicated that canal thresholds could be
accounted for by a model of central processing
consisting only of an optimal processing of
afferent firing rates in additive noise with
no necessity for peripheral dead zone non-
linearities. Quantitative models of threshold
detection were developed which correctly pre-
dicted threshold levels (75% correct detection)
and response latencies for rotational stimuli
It was found that the same detector could be
used to model the threshold responses resulting
from translational stimuli.

The illusions of static orientation were studied
and it was shown that they were consistent with
a simple vector transformation which could be
associated with differences in the processing
of signals arising from stimuli in and stimuli
perpendicular to the "utricle plane". A model
was developed which incorporated this differ-
ence and which was capable of predicting the
perception of orientation in an arbitrary
static specific force environment.

The problem of integrating information from
the semicircular canals and the otoliths to
predict the perceptual response to motions
which stimulate both organs was studied. A
model was developed which was shown to be
useful in predicting the perceptual response
to multi-sensory stimuli.

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3.2   EYE MOVEMENT RESEARCH

A number of improvements in the sampled data model for eye tracking movements have been included in a revised hybrid model based on experimental results in our laboraotry and elsewhere. This hybrid model considers the stochastic nature of this system (characteristic of any biological system) and shows how the observed classes of eye movement response to a given input stimulus can be predicted on the basis of random distributions of synchronization between the timing of the sampler and the occurence of a target transient input.

These improvements are discussed in the following paper.

A REVISED STOCHASTIC SAMPLED DATA MODEL FOR EYE TRACKING

L.R. Young, J.D. Forster, N. Van Houtte

ABSTRACT

Our sampled data model is revised by changing the pursuit system to be continuous and pro- portional to target rate. Transient responses of the model are shown to agree in detail with observed classes of eye movements. Target- synchronized and non-synchronized sampler control logic are compared. Predicted latency distri- butions of a non-synchronized sampler with unknown intersample time distribution are analyzed and saccade synchronized input exper- iments are compared with predicted main model responses. The results show properties of both types of sampler control logic. The assessed limitations and extensions of the model are discussed. The sampled data model proves to be a useful tool in predicting eye movement response based on target movement only.

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Much of this work was carried out by J.D. Forster.
He investigated the classes of outputs which arise from
varying the timing of an input in relation to the sampling
intervals. Target-synchronized and non-synchronized sampler
control logic for the model were investigated by probabilistic
analysis and simulation of a non-synchronized system, and by
four saccade-synchronized eye movement experiments. These
investigations revealed that both types of sampler control
logic should play a role in a sampled data model for eye
tracking movements.

A saccadic eye movement or saccade is a burst of
muscle force moving the eye rapidly from one angular position
in relation to the head, to another. The purpose of a saccade
in eye tracking movements is to correct position error between
the target and the eye.

The discrete nature of the saccadic eye movement control
system has been well established and several discrete systems
have been proposed, including preprogrammed systems, saturating
systems, digitally controlled systems, and sampled data systems.

Pursuit eye movement consists of the smooth low velocity
eye movements which appear in eye tracking of target movements.
Pursuit eye movements usually do not exceed 30 deg/sec and
appear only when the subject is visually tracking a target.
The purpose of pursuit eye movement is to match eye angular

velocity to that of the target in order to prevent a build-up of error in eye position between possible saccades.

If unsynchronized sampling occurs in the eye movement control system, observed latency distributions must be explainable as a function of the stochastic distribution of intersample times. A careful analysis and simulation of the non-synchronized system lead to the result that latency distributions must be non-increasing except at the lowest latency where they jump from zero to their maximum value. Actual latency distributions do increase, however, for approximately the first 50 msecs of possible latency. Thus if unsynchronized sampling occurs in the eye movement control system, the eye must be able to shorten the sampling interval if a step input is observed when the eye has not performed a saccade for 0.2 sec.

If an input to the revised sampled data model occurs immediately after a saccade, the sample which caused that saccade and the sample which will cause a response to the input will be separated by only one sampling interval. It follows that the intersampling interval and the sampler control logic would be revealed by the distributions of response form for inputs occurring at small constant times after a saccade. Four such saccade-synchronized inputs were performed. The results show responses corresponding to both target-synchronized and non-synchronized sampling with the predominant type of control logic changing from experiment to experiment.

The sampler control logic to model the results of these experiments would be a free running non-synchronized sampler which can be influenced in phase and frequency depending upon the difficulty of observed target motion.

The results and experiments described here are summarized in the Master's Thesis of J.D. Forster.

A STOCHASTIC REVISED SAMPLED DATA MODEL FOR EYE TRACKING MOVEMENTS

J.D. Forster

Master's Thesis

Department of Aeronautics and Astronautics
1968

ABSTRACT

The sampled data model for eye tracking movements of Young is revised to make the pursuit system continuous and proportional to target rate. Target synchronized and non-synchronized sampler control logic are analyzed. Frequency distributions of latencies to target steps for non-synchronized sampling systems with stochastic intersampling intervals are shown to be strictly non-increasing. Transient responses of the model are shown to agree with classes of observed eye movement including steps, pulses, ramps and step-ramps. Four experiments are performed in which the occurrence of a target step is synchronized to the occurrence of a saccade. The results show responses corresponding to both synchronized and non-synchronized sampling occurring in the eye movement control system. The sampler control logic in a sampled data model for eye tracking movements, therefore, should have a non-synchronized sampler which can be adapted in phase and frequency depending on the target movement.

As a result of this work on eye movements, Professor
Young prepared a paper on the different methods of measuring
eye movements.

RECORDING EYE POSITION

L.R. Young

In: Biomedical Engineering Systems, Clines
and Milsum, eds., McGraw Hill Co, Inc. 1970.

ABSTRACT

Long standing interest in the measurement
of the direction of gaze as an indication
of visual information processing, as well
as the clinical importance associated with
eye movements, has resulted in the develop-
ment of a wide variety of measurement
techniques. In recent years, perfection of
several electronic measurement methods has
eliminated the tedious and often inaccurate
estimation of the older methods and has made
these visual performance measures available
to a great number of investigators. This
chapter reviews the instrumentation problems
and solutions of measuring eye movements.

A newer survey (prepared for the National Institutes
of Health, Task Force on Essential Skills, 1974) has since
been prepared by L.R. Young and D. Sheena.

EYE MOVEMENT MEASUREMENT TECHNIQUES

L.R. Young and D. Sheena

American Psychologist, 30:315-330, 1975;
also to appear in Behavior Research: Methods
and Instrumentation, 1975 in an expanded
form entitled "Survey of Eye Movement
Recording Methods".

ABSTRACT

The number of techniques devised for measurement of eye movements lags only modestly behind the variety of recent applications of eye movement monitoring for research in reading, sleep, neurology, instrument panel layout, advertising, cognitive processing, esthetics, and for aiming devices for quadreplegics and for weapons systems. Periodic reviews of the instrumentation show a continuing development of the technology not only for improvement of known methods but occasionally for the testing of entirely new concepts. Since one of us last reviewed the field (Young, 1970) the eye point-of-regard system has been reduced to a practical instrument, and the double Purkinje image method has appeared as a promising new technique. Advances have also been made in electrooculography, corneal reflection, and contact lens systems. This review covers the major eye-movement measurement techniques according to the basic property of the eye that is being measured and evaluates the pros and cons of each technique.

In further considering some of the more general problems associated with eye movements, including the important non-linear and adaptive characteristics thus far insufficiently explored, we developed a number of basic requirements for any "second generation models" of eye movements. These constraints and requirements were put forth in the paper abstracted below.

PURSUIT EYE TRACKING MOVEMENTS

L.R. Young

ABSTRACT

A simplistic view of the human eye tracking
ssytem recognizes two major modes of track-
ing: rapid saccadic eye movements and smooth
pursuit movements, and assigns complementary
functions to them. The saccadic eye move-
ment system supposedly acts to maintain the
image of the object of interest on the fovea
by a sequence of discrete high velocity
jumps. The smooth pursuit system has been
assigned the role of stabilization of retinal
images, or more particularly matching the
angular velocity of the eye to the velocity
of the object. This view has led to the
development of models by several groups
which treat the saccadic system as a dis-
crete position servo-mechanism. These
models have been useful in predicting the
response of the eye movement system to a
variety of target patterns in a general
manner. They have further stimulated exper-
iments which show their shortcomings in
detail in a number of ways. This paper
deals not with models but with features of
the pursuit eye movement system which are
known at present, and especially with those
characteristics which are still unknown.
It will be seen that the pursuit system is
not a simple, linear, velocity servo based
on retinal error velocity.

The objective of a study undertaken by Syozo Yasui

was to study eye movement control mechanisms in visual

tracking tasks in relation to subjective visual perception.

Targets in illusory motion, caused by vestibular and

optokinetic stimulation, were of particular interest.

Experimental evidence in the oculomotor control field

supports the idea that the eye velocity commands are generated

based on the target velocity relative to the subject (egocentric

velocity) and not on the velocity relative to the retina. However, no egocentric velocity of the object is directly available to the brain. Such an open-loop motion may well lead one to the realm of perceptual psychology, presuming the involvement of the Helmholtz cancellation theory in recreating the egocentric velocity by means of subtracting the oculomotor command signal from the retinal velocity. This recreated velocity is supposed to be a subjective one which can differ from the objective one to a considerable extent, giving rise to what we term illusions.

The motor theory of egocentric localization, which offers a coherent explanation for various visual illusions, may be stated in the present context such that retinal velocity is compensated only for voluntary commands and not for involuntary ones. In the presence of an involuntary oculomotor command this imperfection results in an illusory egocentric velocity sensation.

We postulated that this subjective velocity in turn affects the eye tracking command. An engineering model accounting for the above aspects was proposed, which adopted existing models for the eye tracking servo and vestibular nystagmus. The visual target and vestibular stimulation (angular acceleration of the head) or optokinetic stimulation (moving vertical stripes in the visual background) are two inputs to the system, whereas the eye movement and

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subjective visual perception about the target are the outputs.

This model assumed that the subjective egocentric position of the target is altered directly by apparent change of the subjective "straight ahead". Thus, the subjective egocentric velocity and position are not necessarily consistent in the Euclidian sense, accounting for the paradoxical perception about the target's motion in the oculogyral illusion, for instance.

This research is summarized in the Doctoral Thesis of Syozo Yasui, the abstract of which is given below.

NYSTAGMUS GENERATION, OCULOMOTOR TRACKING
AND VISUAL MOTION PERCEPTION

Syozo Yasui

Ph.D. Thesis

Department of Aeronautics and Astronautics

1974

ABSTRACT

Principal classes of human horizontal eye
movements are studied herein from biocyber-
netic points of view emphasizing functional
relationships.

The classical psychological notion known as
corollary discarge theory for the visual
motion perception is introduced in the study
of the oculomotor tracking system. The
underlying hypothesis is that of perceptual
feedback oculomotor control, in which the
observer produces tracking eye movements on
the basis of his subjective visual percep-
tion of target motion. This is recognized
as a closed loop version of the corollary
discharge theory, describing both perceptual

and oculomotor mechanisms within the same conceptual framework. A model is elaborated with respect to the smooth pursuit tracking system to the point of establishing an experimental basis for testing the hypothesis. Aiming at selectively activating the internal regenerative feedback that emerges from connecting the corollary discharge outflow with the postulated perceptual-feedback path, the experiment incorporates the forced visual tracking of a small foveal after-image undergoing vestibularly-induced apparent motion. Some pertinent subjective visual effects including the oculogyral illusion are discussed along with a possible further servomechanical refinement of this visual oculomotor control model.

The question of predictive oculomotor behavior is investigated in terms of periodic and nonperiodic-input frequency responses with regard to pursuit movements in the visual tracking and also the slow phase component of optokinetic nystagmus (OKN) and of vestibular nystagmus. Pursuit frequency response results are characterized by a conspicuous tendency toward large low-frequency phase lead with increasing stimulus band width. A special type of predictive phase control scheme is suggested in interpreting this input-adaptive pursuit tracking phenomenon. Results for OKN slow phase also show evidence for the oculomotor prediction but with no such phase lead as found in the above pursuit case. This difference indicates the existence of separate central mechanisms controlling these two classes of visually evoked oculomotor reactions, in spite of their similar phenomenological features as apparent in the time domain observation. In contrast, vestibular nystagmus slow phase representing a typical nonvisual oculomotor reflex failed to show a predictive behavior in the frequency range examined.

Nonperiodic-input frequency response characteristics of the saccadic subsystem for visual tracking are evaluated indirectly

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by the use of nonperiodic-input data for
composite (saccade and pursuit) and pursuit
movements determined experimentally above.
The notion of effective saccadic input is
introduced in this computation in order to
assess the intrinsic saccadic frequency
response, considering the dependence of
saccadic response upon the tracking perfor-
mance by the pursuit system. Resultant
non-periodic-input saccadic phase data are
compared with the periodic-input counterpart
in the literature, confirming the predictive
nature of saccadic tracking. Further, both
gain and phase results are discussed in the
light of an existing mathematical model for
the saccadic system.

Behavior of the fast phase in vestibular
and optokinetic nystagmus is investigated
regarding its characteristic relation to
the slow phase movement. To account for the
relevant phenomena observed similarly in
both types of nystagmus, an efferent feed-
forward type model is constructed based on
a simple principle envisioned from the
experimental results, and tested by a
series of hyprid computer simulations.
This model is intended to predict the fast
phase behavior for a given slow phase motor
information irresptective of its stimulus
modality. This view is reinforced by
clinical nystagmographic data from an
acoustic neuroma patient. Another patho-
logical case cited is central scotomata, in
which reversal of the fast phase direction
occurs with OKN. Dependence of OKN mech-
anism upon central versus peripheral
vision as suggested by this example is
examined in a normla subject by selective
OKN stimulation to the peripheral retina,
based on a computer graphic method for
stimulus presentation coupled with feedback
blanking signal from the eye movement
monitor.

Two additional papers on this work are currently in press. They are abstracted here.

EYE MOVEMENTS DURING AFTER-IMAGE TRACKING
UNDER SINUSOIDAL AND RANDOM VESTIBULAR
STIMULATION

S. Yasui and L.R. Young

ABSTRACT

Vestibular nystagmus was measured during
rotation about a vertical axis in the
dark (eyes open) and while subjects at-
tempted to fixate a foveal after-image.
The after-image inhibited saccades and
increased the slow phase velocity of the
vestibulo-ocular reflex. This gain in-
crease supports the hypothesis of smooth
eye movements based on perceived target
velocity, rather than retinal slip.
Comparison of vestibular nystagmus fre-
quency response for sinusoidal and
pseudo-random stimuli yielded the same
effect of after-image tracking. Further-
more, unlike the visual tracking case,
vestibular nystagmus does not show any
sign of prediction based on stimulus
periodicity.

PERCEIVED VISUAL MOTION AS EFFECTIVE
STIMULUS TO THE PURSUIT EYE MOVEMENT
SYSTEM

S. Yasui and L.R. Young

Science (in press, 1975)

ABSTRACT

Human eye tracking of a foveal after-
image during angular oscillation in the
dark produced smooth eye movements ex-
ceeding those for normal vestibular
nystagmus, and a reduction in the fast
phase. Results support a closed loop
extension of the corollary discharge
theory, with oculomotor commands based
on perceived object velocity.

In a totally different approach to utilization of
eye movement recording, a study was conducted by Dilip
Mathur on human information processing. This study is
summarized in his thesis.

ORGANIZATION OF INFORMATION PROCESSES

D.K. Mathur

Master's Thesis
Department of Aeronautics and Astronautics
1970

ABSTRACT

Eye movements of a subject viewing a scene were
recorded along with his post viewing description
of it. The scanning record and the verbal des-
cription were examined for information about the
process whereby the elements of a scene are fix-
ated and organized into a picture. It appears
that the eye is guided to the element for fixa-
tion by peripheral vision. The distribution of
dwell times between the elements obtained from
the scanning record matches closely the distri-
bution of attention in the verbal description
indicating a strong connection between the two.
The elements of the scene are organized by the
selection of one element as a nucleus and the
association of the others to it. The nucleus

is characterized by a long dwell time for each look and a small number of total looks. The associative elements are all similarly processed although the processing is time-scaled according to their importance. The understanding of the scene is indicated when a logical scanning sequence between the elements is achieved.

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MEDICAL APPLICATIONS

4.1 ORTHOPEDIC DISPLAY

As an outgrowth of our work on integrated displays, the application of hybrid computer displays in clinical studies was investigated. Specifically, in the study of pathological movements, the orthopedic surgeon requires accurate information concerning limb movements and associated muscular activities (EMGs). With this in mind, it was thought useful to provide the surgeon with a film of the subject's limb with a measure of EMG superimposed directly over each muscle of interest, in each frame of the movie film. Thus for continuous viewing or frame-by-frame analysis, the surgeon can see exactly which muscle group is active at every phase of a complex motion such as walking, and decide upon appropriate remedies.

To achieve this result, Mrs. H.L. Galiana worked out a three step process.

1. The subject is filmed, with a 16 mm movie camera while a signal synchronous with the frame rate and the EMG signals broadcast from a telemetry unit around his waist are tape recorded.

2. The film of the subject is scanned to store on DECtape the relative positions of each muscle in each frame. This was done by projecting each

frame onto the screen of an oscilloscope to cover an area 6 x 8 cm, and with the aid of a joy stick and a contact switch and suitable hybrid programming, storing each (x,y) coordinate on DECTape.

3. The hybrid computer system was programmed to generate a display of vertical vectors on the CRT, covering an area 6 x 8 cm. The length of each vector is proportional to its associated full-wave rectified/low-pass-filtered EMG (on the tape recorder) and its lower point is positioned according to the stored coordinates on the DECTape. The choice of coordinates and EMG analysis are synchronized in time using the frame sync signal on the tape recorder. Simultaneously, the changing display is recorded on film with the 16 mm camera, where the camera sync now triggers the beginning of each displayed frame, at the same frame rate as in step 1.

The films of the subject and display are sent to a photographic lab for superimposition, to produce a film of synchronized data and movement. This work was done in conjunction with Dr. Donald Pierce of the Massachusetts General Hospital.

CLINICAL APPLICATIONS OF SYNCHRONIZED PHOTO-
GRAPHY AND HYBRID COMPUTER DISPLAYS

H.L. Galiana

Man-Vehicle Laboratory Report, 1970.

ABSTRACT

The application of hybrid computer displays
to clinical studies has been investigated.
Specifically, in the study of pathological
movements, the orthopedic surgeon requires
accurate synchronized information on limb
movements and associated muscular activities
(electromyograms, EMGs). Such data can then
be used by the physician to help in prescrib-
ing any appropriate surgery or physic-therapy.
The same approach can further be applied to
study the patient's subsequent progress.

To date, most techniques to obtain the
desired information have involved either
recording EMG's on the sound track of a
movie film or using split-frame photo-
graphy to record on film simultaneously
the subject and the EMG traces from a CRT
screen. The subject is usually instrumented
with surface electrodes (or others) connected
via an overhead boom to preamplifiers and
a CRT-camera system on a trolley. However,
the resulting film is usually unsuitable
for single frame viewing, since only a few
cycles of the EMG can be observed on each
frame.

This report presents a possible alternative
using a hybrid computer-controlled CRT dis-
play, which could be applied to any instance
where synchronous visual and bioelectric
and/or physical information is required.
The overhead boom is replaced with telemetry,
thus freeing the subject for more complex
movements. Furthermore, the recorded data
is subsequently manipulated on a hybrid
computer (PDP-8/GPS 290T) to produce any
desired display on a CRT screen. The films
of subject and CRT display are processed
to produce a movie film of synchonized
full-frame superimposed movements and data.
Increased versatility is obtained at the
cost of increased film and data processing.

Such an approach would be valuable not only in clinical diagnosis but also in basic research studies. The computer display can be made to represent forces, torques, temperature, EMGs, etc, in any desired form or combination. The complexity of the display is only limited by the results of a trade-off between the desired display frame rate and the cycle time of the necessary calculations.

4.2 MITNYS I AND II

The addition of Dr. Alfred Weiss to our laboratory encouraged clinical applications of our vestibular research. One such area examined was the use of galvanic stimulation of the vestibular apparatus. Under the supervision of Dr. Wiess, John Tole, using the laboratory's single axis rotating chair and eye movement monitoring apparatus, worked to develop models for vestibular galvanic stimulation. This work is summarized in his Master's thesis, the abstract of which is given below.

GALVANIC STIMULATION AND THE PERCEPTION OF ROTATION

J.R. Tole

Master's Thesis

Department of Aeronautics and Astronautics

1970

ABSTRACT

The influence of galvanic vestibular stimulation on the perception of rotation was investigated. The study was intended to lay the groundwork for future, more detailed

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study of the galvanic reaction. Of particular
interest are possible clinical applications in
the treatment of vertigo and the diagnosis of
certain vestibular disorders. A set of experi-
ments was designed to measure the gross effects
of current intensity and point of application
on a subject's perception of rotation. An ap-
proximate threshold for the intensity effect
was determined. Among points of application
only polarity difference could be shown to be
significant. A tentative linear relation
between the bias in perception threshold and
the intensity of current was found. The gal-
vanic reaction of one vestibularly abnormal
subject is also discussed.

Comparisons were made between galvanic stimu-
lation and other common means of vestibular
stimulation. Current mathematical models of
vestibular function were reviewed and the
extension of these models to include the gal-
vanic reaction was examined. Possible future
directions for research in this area are also
discussed.

During this period, a major program was written for the

analysis of nystagmus. In addition to frequency and duration,

two pieces of information from a nystagmus record are of interest

to many researchers. One is cumulative eye position, i.e. the

total eye movement if all the fast phases are removed and the

slow phase segments pieced together. The other is the velocity

of the slow phase portion.

In the past this information has been extracted from

eye movement record by hand, an extremely tedious task. We

have developed a hybrid computer program which processes an

analog eye movement record to provide nearly continuous slow

phase eye velocity. It was developed primarily for use in

on-line feedback experiments with a human operator, but it is

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equally valuable as a data reduction tool for any nystagmus record.

Three papers have been published concerning this program, along with a Laboratory report on the actual operation of the program. The papers are abstracted below:

MITNYS. A HYBRID PROGRAM FOR ON-LINE ANALYSIS
OF NYSTAGMUS

J.R. Tole and L.R. Young

Aerospace Medicine 42:508-511, 1971.

ABSTRACT

A computer program, MITNYS, has been developed for on-line analysis of nystagmus during closed loop experiments involving visual and/or vestibular function. The program accepts voltage records of eye position and yields cumulative slow phase position and continuous slow phase velocity nearly instantaneously. The slow phase velocity is obtained by differentiating the calculated cumulative position rather than the raw eye movements.

While intended primarily for experimental work, the program is also useful as a data reduction tool. The algorithm is discussed in some detail. It can be implemented on a hybrid computer or a small digital computer with 2 channels each of analog to digital and digital to analog converters. An example of a vestibular nystagmus record processed with MITNYS is included.

MITNYS II: A DIGITAL PROGRAM FOR ON-LINE ANALYSIS
OF NYSTAGMUS

J.H.J. Allum, J.R. Tole, A. Weiss

IEEE Transactions on Biomedical Engineering,
BME-22:196-206, 1975

ABSTRACT

A digital computer program, MITNYS II, has been
developed for on-line analysis of nystagmus which
results from visual, vestibular or caloric stimu-
lation. The program accepts sampled records of
eye position and yields comparative slow phase
position, slow phase velocity, instantaneous fast
phase frequency and other parameters in 25 msecs.
In this paper, the algorithms by which fast phases
are detected, and by which slow phase cumulative
eye position is extrapolated across the fast phase
interval are described. Extensive tests with
vestibular, optokinetic and caloric nystagmus
yield reliability figures of the order of 2% for
false identification of fast phases and missed
fast phases. MITNYS II has been successfully
employed to interpret clinical EOG records,
examples of which are presented.

A LEAST MEAN SQUARES CUBIC ALGORITHM FOR ON-LINE
        DIFFERENTIAL OF SAMPLED ANALOG SIGNALS

J.H.J. Allum

ABSTRACT

A digital computer algorithm is developed for on-line
time differentiation of sampled analog voltage signals.
The derivative is obtained by employing a least mean
squares technique. The recursive algorithm results
in a considerable reduction in computer time compared
to a complete new solution of the normal equations each
time a new data point is accepted. Implementation of
the algorithm on a digital computer is discussed.
Examples are simulated on a DEC PDP-8 computer.

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EQUIPMENT

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5.1 ROTATION SIMULATOR

To rotate subjects for stimulation of the semicircular canals, and to tilt them with respect to the gravity vector in a precise controllable manner, we first made use of the NE-2 simulator provided by the NASA Ames Research Center. Installation and wiring of the equipment at M.I.T. was followed by extensive mechanical and electrical modification to make it a more accurate research tool, which served us well through a decade.

5.2 SINGLE AXIS ROTATING CHAIR

A rotating chair simulator was designed and constructed. The chair portion is an entirely enclosed box in which the subject sits upright, seeing no external references. His head is supported by a head rest and his mouth fixed to a bite board. He may wear photoreceptor spectacles or surface electrodes to monitor eye nystagmus and he may manipulate a joystick to exercise closed loop control of chair velocity. Leads are brought out through slip rings. His head is positioned above the axis of rotation.

The chair is rotated about a vertical axis by two 7½ ft-lb torque motors connected directly to the shaft of the chair. This amount of available torque will allow the chair to be driven with a sinusoidal acceleration whose peak ranges from

10 degrees/sec^2 to 100 degrees/sec^2 at any frequency in the range 0.01 cps to 1 cps. A single speed resolver is used for closing a position feedback loop. In open loop operation the number of revolutions is unlimited, and the chair can be operated at constant velocity or acceleration. The simulator was used to extend the experimental results of Hixon and Niven on non-linear effects in nystagmus phase and to investigate the thresholds of perception and nystagmus for angular acceleration. It was also used in early experiments on rotation sensation associated with galvanic stimulation, first attempts at visually induced motion effects and correlation of directional preponderance for subjects who had previously been involved in caloric tests of their vestibular system.

Additionally, this rotating chair was placed on the 32 foot radius centrifuge of the M.I.T. Instrumentation Laboratory for counter-rotating experiments to test some of our fluid dynamic models of cross coupling in the canals.

5.3   LINEAR ACCELERATION CART

To stimulate the linear acceleration sensors without any rotation of the subject, we designed and constructed a single-axis linear acceleration cart with a 32 foot horizontal throw, maximum acceleration of 0.3 g's, threshold of 0.001 g's and nearly 1 cps bandwidth. This simulator was constructed on a very limited budget using   surplus material. However, its potential was successfully demonstrated in a number of experiments, and further modifications increased its utility.

THE DESIGN AND CONSTRUCTION OF AN ACCELERATION
CART

R.J. Schulte and R.E. Vreeland, Jr.

Master's Thesis

Department of Aeronautics and Astronautics

1965

ABSTRACT

This thesis presents a discussion of the problems
encountered in designing and constructing a sim-
ulator to determine human vestibular response to
a range of linear accelerations from 0 to 0.3 g's.
Starting with a set of initial performance speci-
fications, the designers have combined an array
of commercially available components into a system
which, although requiring further refinement before
completion, shows considerable promise of fulfilling
the initial requirements.

The resulting system consists of a wheeled vehicle
driven by a cable and drum arrangement, powered
by a hydraulic-electric servo-valve. Technical
design considerations are presented along with
a discussion of the "trade-offs" between various
component options. A description of the system
characteristics as well as an analysis of pre-
liminary test results and recommendations for
future system improvements are included.

5.4 STABILIZED MOTORBIKE

As a test vehicle in which visual and motion cues are
used for dynamic orientation, we instrumented a motorbike.
We measured tilt angle from apparent vertical and steering
deflection to identify the rider's control function, and
also developed stabilization to attempt to duplicate the
rider's performance.

5.5   COMPUTER SYSTEM

Many of our experiments required a digital computer for data reduction. At first we recorded data directly on FM analog tape, converted it to punched cards in the A/D converter of the GE-225 computer in the Electronic Systems Laboratory, and ran the programs on the IBM 7094 of the Computation Center or the IBM 1620 of the Department of Aeronautics and Astronautics. Later, programs were written to use the TX-0 computer to convert data directly to digital tape, and the installation of a time sharing console adjacent to our laboratory facilitated the process.

A SHARE program for spectral analysis and describing fucntion calculations was modified for our purposes, and programs were written to determine phase plane switching lines associated with the human's non-linear control characteristics. Finally, we specified and installed a laboratory hybrid computer system for simulation, on-line experiment control and data analysis.

Our hybrid computer system was continually improved both in hardware and software. Additional channels of D/A conversions were installed and the operating system of the

PDP-8 computer was modified to make full use of the capabilities of the DEC-tape data storage system. These and other modifications were described in a paper by N. Van Houtte and C.M. Oman presented at the DECUS Spring Symposium at Atlantic City, New Jersey, May 1970. The abstract of that paper follows.

THE M.I.T. MAN VEHICLE LABORATORY PDP-8 PROGRAMMING SYSTEM

Noel A.J. Van Houtte and Charles M. Oman

ABSTRACT

During the past three years, users of the DECUS 8-64 DECtape programming system at the M.I.T. Man Vehicle Laboratory have more fully debugged the routines, and made some modifications which make them more flexible. The 8-64 system is presently the only all DECtape system generally available for use with the 552 DECtape control. Major improvements include: modifications to the symbolic editor and PAL III input and output routines allowing access to a number of tape drives, complete protection for system files, and a feature allowing optional listing of the tape directory. Additional programming notes are also included on changes to the PAL III and FORTRAN II instruction sets, and on operations involving series and factorial computations using Digital 8-10S CALCULATOR.

Van Houtte and Oman also presented a paper at that symposium on our display generating techniques, the abstract of which follows:

HYBRID COMPUTER DISPLAY TECHNIQUES INVOLVING A PDP-8

Noel A.J. Van Houtte and Charles M. Oman

ABSTRACT

The hybrid facility in the M.I.T. Man Vehicle Laboratory, consisting of a PDP-8 and a GPS-290

has been used to develop a linear perspective image of a three-dimensional object.

The presentation of the image on a large screen CRT tube looks like the scene an aircraft pilot would see if he were looking out the cockpit window.

The role of the digital computer is to keep track of the coordinates of reference points in inertial space, taking into account the motion of the simulated aircraft, and to compute the information received for the display.

The analog part of the facility takes this display information by an interrupt request and draws the picture.

Intitial development of the display was done using a cube as the displayed object. The system has also been used to produce a contact analog display for a VTOL aircraft landing under Category III conditions.

The Link GAT-1, the latest of our moving base simulators, was used for our display research and had increasing use both as a disorientation device and for measurement of pilot workload. Bypassing the internal computer, we now run the device as a general purpose moving base simulator through our hybrid computer.

5.6   HEAD POSITION MONITOR

As a part of our work on displays, we found it necessary to monitor head position. An accurate, simple system was required, one which did not encumber the pilot's head. Experimentation was done with an ultrasonic sound transmitter mounted on the pilots' helment. If two ultrasonic receivers are mounted on either end of a polystyrene rod mounted over-

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head and the transducer is pulsed periodically , the difference between the arrival times of the transmitted pulse at the two receivers is proportional to the distance of the transmitter to the center of the rod, measured along the axis of the rod. A prototype system was constructed utilizing several inexpensive transducers, cemented directly to the rod to minimize the loss in amplitude of the received waveform. This system proved to be too directional for this application and modifications were undertaken to design a more optimal setup.

Our next attempt at head position monitoring was a system which consisted of a light source mounted on a head band worn by the subject. A lens and two silicone photocells were mounted 84 inches above the light and masked so that the light source threw a rectangular patch of light onto the two photocells, yielding an output voltage proportional to the light position, which was suitable for processing by the analog computer and A/D conversion in our 3-D display system. The monitor when tested over a range of ± 10 cm head position, had an accuracy of 4.5% of full scale. Further work on head position monitoring included EMG measures from neck muscles (VON RENNER) and development of a three-axis helmet mounted photoelectric system (CHOUET).

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